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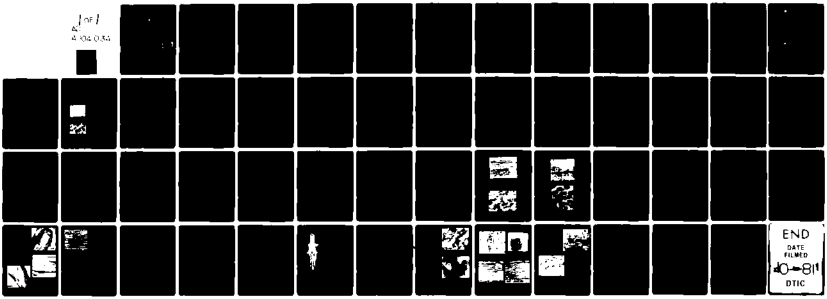

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The interface between a current carrying copper wire brush and a copper slip ring has been characterized for vacuum and wet CO_2 (1 atm) rotation with respect to electrical contact resistance, friction, and chemical composition (Auger electron spectroscopy). In addition scanning electron microscopy was used to characterize the surfaces of the slip ring, wire brush, and wear particles. The latter were also studied by x-ray diffraction and transmission electron diffraction methods. The results are embodied in 4 papers attached to this report.

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ANNUAL REPORT

October 1, 1980 - September 30, 1981

SURFACE PHYSICS AND CHEMISTRY OF ELECTRICAL CONTACT PHENOMENA

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SUMMARY

The objectives of this research can be divided into two parts. One part was concerned with the improvement of the slip ring-brush assembly, additions of a prototype debris collection system and a stainless steel gas handling system to introduce dry and wet CO_2 environments in the vacuum system. The other part of our research dealt with investigations carried out on the microstructural characterization of rotating Cu-Cu electrical contacts in vacuum and wet CO_2 environments. The main achievements and results of the past year are listed in the appendices as papers published and accepted for publication.

The work mainly consists of investigating the chemical, electrical and wear properties of the rotating interface between OFHC Cu slip ring and two high purity Cu wire brushes *in situ* in ultra high vacuum and in one atmosphere of wet CO_2. The chemical composition of the slip ring surface was determined by Auger electron spectroscopy (AES). The contact resistance was measured by a potentiometric four point probe technique while the wear properties of the interface and the morphology of the debris were studied by frictional force, scanning electron microscopy (SEM), transmission electron diffraction (TED), and X-ray diffraction (XRD) measurements.

I. REPORT

A. Research Results

The success achieved during the last year in characterizing the OFHC Cu slip rings that rotate in contact with two high purity Cu wire brushes in vacuum and in one atmosphere of wet CO_2 are reported in the Appendices to this report. The main achievements of our findings reported in these papers are as follows:

In vacuum, the initial conventionally cleaned slip ring surface (Cu 50 a/o) became almost completely clean (98 a/o) after several hundred rotations. Carbon was the major impurity observed. The contact resistance decreased with increasing number of slip ring revolutions and its stable value was around 1-2 mΩ and depended on the magnitude of the contact force. The frictional force also increased substantially as the rotation proceeded and finally after many hundreds of revolutions the slip ring stopped rotating because of excessive friction and ultimate cold welding. The average coefficient of friction (μ) increased more than four times and just before cold welding its value was around 1.5.

In the case of rotation in wet CO_2 the surface also became clean except for the development of a slight S and C contamination. Sulfur came from an impurity in the CO_2 gas and the carbon concentration was of the same order as that observed in the vacuum experiments. Thus running in wet CO_2 contributed no additional C to the surface. The frictional force decreased as the rotation proceeded and cold welding did not occur. CO_2 and water were adsorbed on the surface and acted as a good lubricant. The contact resistance also decreased as the number of slip ring revolutions increased,but its steady state value was invariably higher than that measured in vacuum experiments for the same magnitude of brush normal force. Higher normal forces have lower contact resistances.

Likewise, the thickness of the H_2O-CO_2 interfacial layer depended on the contact pressure. Thus the interfacial resistance appears to arise possibly from a combination of quantum mechanical tunneling through the CO_2-H_2O layer as well as occasional direct brush-slip ring contact. An approximate calculation based on a tunneling conduction mechanism resulted in an interfacial film thickness of about 6 Å for which the measured contact resistance was 2.2 mΩ and the normal force was 80 gms. These values could easily arise from a one to three molecule thick layer of CO_2-H_2O.

The most significant conclusion based on these results is that the contact resistance at the Cu-Cu interface in wet CO_2 is not due to contamination by carbon or other impurities, but rather arises from the presence of this H_2O-CO_2 layer at the interface. The low contact resistance in vacuum arises from direct metal-metal contact, which resulted in the formation of large wear particles. The contact resistance decreased during rotation mainly because the initial surface impurities were buried during rotation or possibly partially removed by the fallen wear particles. Also heavy plastic deformation at the interface would cause the surface contact area to increase, thereby decreasing the interfacial resistance.

In vacuum, deep ridges arise from brush end ploughing and from random localized welding of brush wire ends to the slip ring during rotation, resulting in tensile plastic deformation of the weld and then final fracture of the weld material or wire. Continued rotation may pull out some of these broken wire ends or pieces of slip ring material, which then roll over and over between the brush-slip ring interface and eventually fall away from the interface. The morphologies of the wear particles were all more or less the same. Some are made of thin layers rolled as sheets and some with more compacted but still

rolled surfaces. The results from X-ray diffraction studies of large particles were identical to those obtained by TED from small particles. The diffraction patterns consisted of typical powder patterns and did not show any preferred orientation.

B. Equipment Design and Fabrication

A stainless steel ultra high vacuum system of low 10^{-10} torr range capability was used to characterize the Cu-Cu slip ring-brush interfaces. The brush-slip ring assembly was mounted on a specimen manipulator capable of X, Y, Z displacements, and rotation by an external motor. The UHV system included an Auger cylindrical mirror analyzer (CMA), a 3 keV sputter ion gun and a 90^{0} magnetic sector partial pressure analyzer.

The Auger electron spectrometer which was used to examine the surface tracks was fully controlled by a Hewlett Packard 9825A desk top computer and multiprogrammer. A stainless steel gas line was attached to the system to introduce wet CO_2 into the chamber by bubbling it through a doubly distilled H_2O/CO_2 solu-ion in a stainless steel trap. A molybdenum sheet tray was placed inside the vacuum chamber under the brush-slip ring assembly to collect wear particles during contact rotation. Complete details of the equipment are given in the attached papers.

C. Personnel and Activities

Dr. Richard W. Vook, Professor of Materials Science, acted as Principal Investigator on the project. He was assisted by Dr. Bhoj Singh, a full time Research Associate, Mr. B. H. Hwang, a full time graduate research assistant and Mr. J. G. Zhang, a visiting research scientist, all in the Department of Chemical Engineering and Materials Science. Mr. Zhang joined the project in August 1980. Mr. Hwang left the project in May 1981 after receiving an M.S. in Materials Science. Several lectures were given at various meetings and they are listed in Section III.

II. PUBLICATIONS OF ONR SUPPORTED RESEARCH: 1978 - PRESENT

1. "Elemental Surface Composition of Slip Ring Copper as a Function of Temperature," R. W. Vook, B. Singh, E.-A. Knabbe, J. H. Ho, and D. K. Bhavsar, Electrical Contacts, 1979 (I.I.T. Chicago), 17-21 (1979)
and
IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. CHMT-3, 9-12 (1980).

2. "AES Study of Sulfur Segregation on Polycrystalline Copper," B. Singh, R. W. Vook and E.-A. Knabbe. Read at the 26th AVS Symposium held in New York, Oct. 1-5, 1979, Jour. of Vac. Sci. and Tech., 17, 29-33 (1980).

3. "*In Situ* AES Characterization of Rotating Electrical Contacts," B. Singh and R. W. Vook, Electrical Contacts, 1980 (I.I.T. Chicago), 53-58 (1980).
and
IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. CHMT-4, 36-40 (1981).

4. "Interfacial Characterization of Copper Slip Ring-Wire Brush Contacts," B. Singh and R. W. Vook, Proceedings of the 8th International Vacuum Congress at Cannes, France, Vol. II, Vacuum Technology and Vacuum Metallurgy, 441-444, 1980, (Suppl. a la Revue << Le Vide, les Couches Minces >> #201).

5. "Characterization of Copper Slip Ring-Wire Brush Electrical Contacts", B. Singh, B. H. Hwang and R. W. Vook, Accepted for publication in Vacuum TAIP (G.B.), (1981).

6. "*In Situ* AES Characterization of Wet CO_2 Lubricated Sliding Copper Electrical Contacts," B. H. Hwang, B. Singh, R. W. Vook and J. G. Zhang, Accepted for publication in Electrical Contacts 1981 (I.I.T. Chicago) (1981).

7. "Microstructural Characterization of Rotating Cu-Cu Electrical Contacts in Vacuum and Wet CO_2 Environments," B. Singh, J. G. Zhang, B. H. Hwang and R. W. Vook. To be read at Advanced Current Collection Conference (I.I.T. Chicago), 1981, Submitted to Wear, 1982.

III. LECTURES, SEMINARS, PRESENTATIONS FOCUSING ON ONR SUPPORTED RESEARCH

1.	Jan. 15-16, 1979	Third DARPA workshop on Advanced Current Collection, Coral Springs, Florida, "Surface Physics of Electrical Contact Phenomena."
2.	Sept. 10-12, 1979	25th Holm Conference on Electrical Contacts, I.I.T. Chicago, "Elemental Surface Composition of Slip Ring Copper as a Function of Temperature."
3.	Oct. 2-5, 1979	American Vacuum Society Symposium, New York, NY, "AES Study of Sulfur Surface Segregation on Polycrystalline Copper."
4.	Oct. 24-26, 1979	Fourth DARPA workshop on Advanced Current Collection , Pittsburgh,PA, "Slip Ring and Film Evaporation,"
5.	Sept. 22-26, 1980	Eighth International Vacuum Congress-Vacuum Technology and Vacuum Metallurgy, Cannes, France, "Interfacial Characterization of Copper Slip Ring-Wire Brush Contacts.
6.	Sept. 29-Oct 1, 1980	26th Holm Conference on Electrical Contacts, I.I.T. Chicago, "*In Situ* AES Characerization of Rotating Electrical Contacts", Written presentation only.
7.	Jan. 6, 1981	Fifth DARPA Advanced Current Collection workshop, Pittsburgh, PA, "SEM/AUGER Studies at Syracuse University."
8.	Sept. 21-23, 1981	27th Holm Conference on Electrical Contacts, I.I.T. Chicago, "In Situ AES Characterization of Wet CO_2 Lubricated Sliding Electrical Contacts."
9.	Sept. 23-25, 1981	Advanced Current Collection Conference, Chicago, "Microstructural Characterization of Rotating Cu-Cu Electrical Contacts in Vacuum and Wet CO_2 Environments."

APPENDIX I

IN SITU AES CHARACTERIZATION OF ROTATING ELECTRICAL CONTACTS

by

B. Singh and R. W. Vook

IEEE Transactions on Components, Hybrids, and Manufacturing Technology, 4, 36-40 (1981).

In Situ AES Characterization of Rotating Electrical Contacts

BHOJ SINGH AND RICHARD W. VOOK

Abstract—The electrical contact resistance and surface chemical composition of a rotating copper slip ring in contact with two wire brushes were investigated *in situ* under ultrahigh vacuum (UHV) conditions as a function of the number of revolutions of the slip ring. The initial surface of the copper slip ring was examined by Auger electron spectroscopy (AES) techniques and found to be almost completely covered by surface impurities largely consisting of carbon. As the slip ring was rotated in contact with the brushes, the impurity concentration declined sharply to less than ten at% after several hundred revolutions. A corresponding decrease in electrical contact resistance and a sharp increase in friction and wear were also observed. Regardless of polarity, the brush with the higher contact pressure had the lower contact resistance. The *in situ* experiments were terminated when the motor turning the slip ring could no longer overcome the adhesive forces between the brushes and slip ring. Subsequent scanning electron microscopy observations of the brush and slip ring surfaces gave supplementary information on the mechanisms of friction, wear and surface cleaning during rotation. For a given experiment the change in contact resistance during rotation divided by the change in impurity concentration on the surface of the slip ring is approximately the same for the positive and negative interfaces. This parallelism of contact resistance and surface impurity concentration suggests that the former is caused to a significant extent by the latter. Since the surface impurities are mostly carbon atoms, it is concluded that carbon impurities are largely responsible for the observed contact resistance.

INTRODUCTION

MOST PREVIOUS studies of electrical contact phenomena have been concerned with experiments carried out under normal or near normal atmospheric pressure conditions because those are the conditions of principal commercial importance [1]. Recent workers in this area, however, have used controlled environments such as humidified carbon dioxide [2], [3], humidified air, and helium [4]. In a few cases ultrahigh vacuum (UHV) techniques have been used to study adhesion and contact resistance under clean surface or carefully contaminated surface conditions [5]-[9].

In the present experiments *in situ* measurements were made on a copper slip ring rotating in contact with two copper wire brushes [3] running on different tracks under ultrahigh vacuum conditions. The average electrical contact resistance of each brush-slip ring interface was measured along with the chemical composition of the surface of the slip ring as a function of the number of revolutions. Subsequent examination of the contact surfaces by scanning electron microscopy was also carried out. The results allow correlation of contact resistance with interfacial chemical composition.

Manuscript received May 30, 1980; revised October 23, 1980. This work was supported by the Office of Naval Research under Contract N00014-79-C-0763. This paper was presented at the 26th Annual Holm Conference on Electrical Contacts, Chicago, IL, September 29–October 1, 1980.

The authors are with the Department of Chemical Engineering and Materials Science, 409 Link Hall, Syracuse University, Syracuse, NY 13210.

EXPERIMENTAL DETAILS

A stainless steel ultrahigh vacuum system was used to investigate electrical contact phenomena associated with rotation of a copper slip ring in contact with two copper wire brushes running on different tracks. Residual pressures in the low 10^{-9}-torr range were obtained in the unbaked system after several days of pumping by an arrangement consisting of a titanium sublimation pump and a Vac-ion pump.

Fig. 1 shows the arrangement of the slip ring which rotates in contact with two Cu wire brushes. The brushes are pressed against the slip ring by means of a stainless steel spring that is electrically insulated with ceramic beads. The brushes can be removed from the contacting slip ring surface by manipulating two linear-rotary vacuum feedthroughs. The slip ring is axially attached to a magnetically coupled rotary feedthrough, which is turned by an ac motor coupled to it by a rubber belt. The slip ring is composed of oxygen-free high conductivity (OFHC) (99.98 percent) Cu and the brushes each consist of 362 0.127-mm (0.005-in) diameter 99.999 percent Cu wires.

The temperature of the interface is monitored in an approximate way by a copper-constantan thermocouple (TC) included in brush 1. The thermocouple junction is located about 1 mm from the interface to avoid contact and possible surface contamination. It is electrically insulated by means of glass wool sleeving. The brushes are screwed to two 14.29-cm long rectangularly shaped (2.54 cm × 1.27 cm) stainless steel electrodes, each having a smooth hinge in the middle. This hinge lets the brush move away from the slip ring but prevents it from collapsing towards the slip ring. These electrodes are then attached to two 9.5-mm diameter OFHC Cu-ceramic vacuum feedthroughs (CL). This arrangement provides a low series resistance to the contact resistances. The voltage leads (VL) are clamped near to each brush to avoid the relatively large and erratic hinge resistance. The brushes are arranged at 180° to each other and axially displaced (1.6 cm) to make separate tracks on the slip ring. The whole brush-slip ring assembly is mounted on a specimen manipulator capable of x, y, z displacements. The UHV system contains an Auger cylindrical mirror analyzer (CMA), a 3-keV sputter ion gun, and a 90° magnetic sector partial pressure analyzer (see Fig. 2).

Before each experiment, the surfaces of the OFHC copper slip ring and the wire brushes were mechanically polished with emery papers down to grit 600-A and then rinsed in acetone

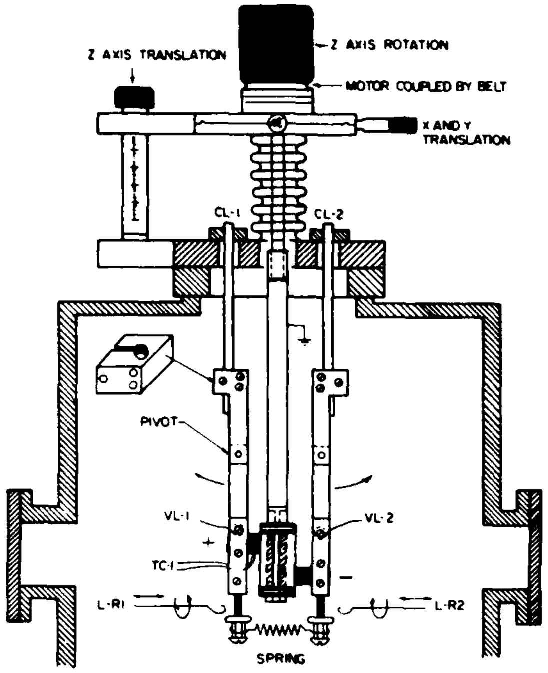

Fig. 1. Schematic of UHV vacuum chamber, rotational feedthrough and slip ring-brush assembly.

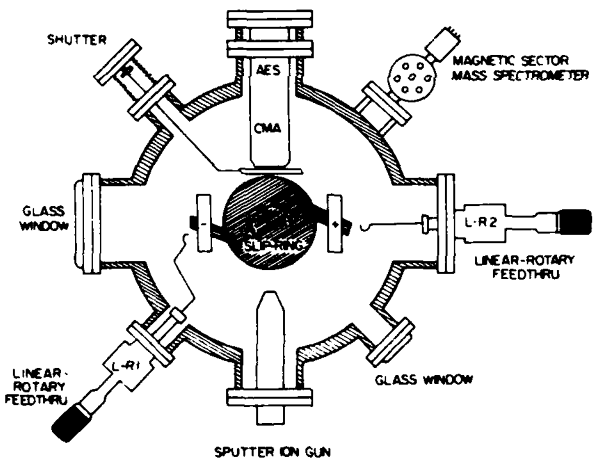

Fig. 2. Top view of slip ring-brush assembly, CMA, sputter-ion gun, mass spectrometer, and other feedthroughs in UHV chamber.

and ethanol. Each brush was mounted with a thin (0.75-mm thick) stainless steel sheet behind it to stiffen it. The end of the stainless steel sheet was located approximately 1 mm away from the slip ring surface.

The slip ring was electrically grounded by means of thick copper wires sliding on the stainless steel axis, the neutral contact. The contact resistances between 1) the positive brush and slip ring and 2) the negative brush and slip ring were recorded on a dual pen recorder. Each measured resistance, therefore, includes a small lead resistance as well as the contact resistance at the brush. Since no appreciable current flowed through the neutral contact, its voltage contribution can be neglected. Experiments were performed with four brush direct currents: 50 mA, 5 A, 30 A, and 32 A. The same current went through both brushes. With the brushes retracted, the slip ring rotated at a speed of about 150 r/min, measured by an optical tachometer. During the experiment, the rotational speed of the slip ring was measured at regular time intervals along with the input power to the motor. The temperature of brush 1 during slip ring contact was automatically recorded on a Honeywell temperature chart recorder at intervals of 30 s.

The CMA of the Auger spectrometer could examine the positive and negative brush traces on the slip ring surface by raising or lowering the slip ring assembly with the bellows-sealed specimen manipulator after the brushes were retracted with the two linear-rotary motion feedthrus. The Auger electron spectrometer was fully controlled by a Hewlett-Packard 9825A desktop computer using a multiprogrammer. Typical Auger traces covering a 50–1300-eV range were directly digitized with an energy increment of 0.65 eV. Computerized values of peak-to-peak heights of the AES signals of various elements were obtained with a precision of one in 2000. These Auger spectra were taken using a primary beam energy of 3 keV, a modulation amplitute of 5 V (peak-to-peak), and a 50-μA beam current. The Auger spectra were taken while the slip ring was rotating and the brushes were retracted, thus giving an average surface composition of the track. Residual gas analyses were also performed before and after the contact resistance measurements were carried out.

After the experiment was over, the slip ring and brushes were removed from the vacuum chamber. SEM pictures were then taken of both the positive and negative surface tracks and also of the brush contact surfaces.

RESULTS

A. Contact Resistance and Friction Measurements

The contact resistance measurements are shown in Figs. 3 and 4 for both positive and negative interfaces and for forward and reverse brush polarity. Clearly, the contact resistance decreases with the increasing number of revolutions at ambient temperature. In addition the curves are more or less parallel to each other indicating that the initial conditions determine whether a curve is "high" or "low." These initial conditions include such variables as surface impurities, brush wire orientation and stiffness, lead resistance, contact force, etc. Also the frictional force increased substantially, resulting eventually in appreciable vibration caused by alternate welding and fracture at the interface. Finally, the motor stopped rotating due to excessive friction. In addition, the rotational speed of the motor driving the slip ring decreased by about 25 percent (from 150 to 115 r/min) while the current to the motor increased by about 20 percent (from 96 to 115 mA) during the experiments.

In Figs. 3 and 4 the circled points indicate the contact resistance R before the slip ring started rotating and after it stopped. It is clear that R did not depend significantly on the angular velocity of the slip ring, since the circled values for a nonrotating slip ring are essentially the same as those obtained when it was rotating. The total number of slip ring revolutions at the time each resistance was measured was calculated from a

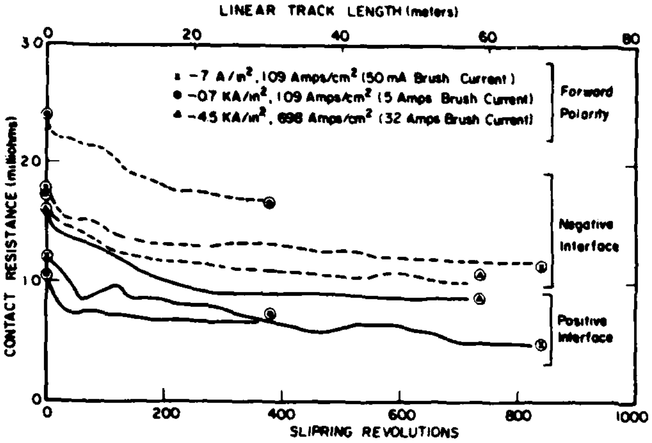

Fig. 3. Average contact resistance versus slip ring revolutions for various current densities. Circles for static and lines for dynamic resistance. Forward polarity.

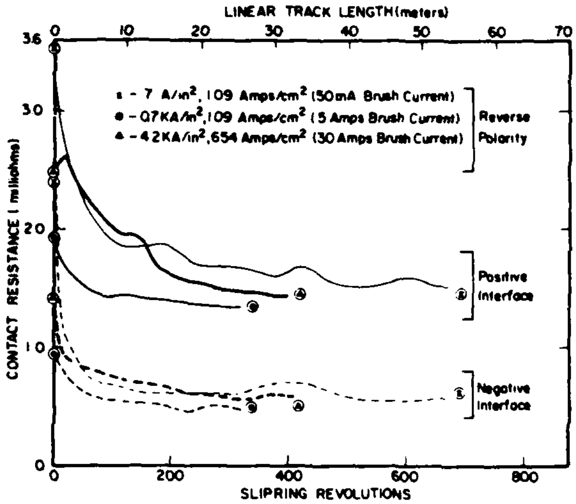

Fig. 4. Average contact resistance versus slip ring revolutions for various current densities. Circles for static and lines for dynamic resistance. Reverse polarity.

graph of the speed of rotation versus time of the experiment. Figs. 3 and 4 also show that the number one brush-slip ring interface (Fig. 1) always had the lower resistance. This result is due to the higher contact force exerted on brush 1. It arises from the manner in which the forces on these brushes are applied. *Ex situ* experiments showed that the forces needed to break electrical contact on brushes 1 and 2 were 2.55 and 1.76 N (260 and 180 g-mass), respectively.

B. AES Results

In each experiment, Auger electron spectra were taken *in situ* from both the positive and negative brush tracks on the slip ring before and after (but not during) the contact resistance measurements. The brushes were retracted during the AES measurements and the slip ring was continuously rotated. This procedure gave the average impurity concentrations of the whole track with only negligible loss in resolution. Peak-to-peak heights of all Auger signals were normalized [10], [11] to fractional atomic surface concentrations without making any other corrections [12], [13]. The observed decrease in the impurity concentration during rotation is given in Table I. The Cu and C concentrations are listed along with the sum of all the impurity concentrations. These impurities consisted of C, S, 0, Cl, N. No clear correlation of final impurity concentration with current or with the positive and negative brushes was observed, suggesting that any possible electromigration effects were not significant in the present study. On the other hand, the change in contact resistance ΔR divided by the change in concentration ΔI of the surface impurities on the slip ring was approximately the same for the (+) and (−) interfaces in each of the experiments.

An additional set of experiments was performed to determine the surface composition of the slip ring as a function of the number of revolutions n, rather than just before and just after the resistance measurements were made. These results showed that the change in impurity concentration with n more or less parallels the change in contact resistance.

At the end of each experiment and before the system was opened to dry nitrogen, AES measurements were made on the rotating slip ring (brushes retracted) to determine the magnitude and nature of impurity buildup on the surface due to the residual gases present in the system. It was found that the concentrations of all the impurities increased only very slightly with time. The rate of increase of the total impurity concentration on the rotating slip ring varied from 0.05 to 0.26 at% per minute. This effect, therefore, has a negligible influence on the results presented in this report. These results along with the temperature increases observed in the number one brush are listed in Table I.

C. Scanning Electron Microscopy

SEM pictures of the brush tracks on the slip ring, taken after the slip ring was removed from the vacuum system, showed that the surface material was smeared out in the track areas, suggesting that the initial surface impurities were buried during rotation. Also small pieces of brush wires W can be seen to be adhering to various places on the slip ring as shown in Fig. 5. The ridges shown in this micrograph lie parallel to the direction of travel. Each ridge arises from random localized welding of a wire to the slip ring during rotation resulting in tensile plastic deformation of the region near the weld area along the direction of motion and eventual fracture of the weld. Continued rotation tends to smooth these areas into ridges. SEM pictures of the brush ends also showed occasional abrupt, broken ends of wires, along with smeared out flat regions also containing ridges, as shown in Fig. 6.

DISCUSSION

A series of experiments in which an OFHC Cu slip ring rotated in contact with a multiwire 99.999 percent Cu brush was carried out under UHV conditions. The current densities used were 1.09, 109, 654, and 698 A/cm^2. Both forward and

TABLE I
COPPER WIRE BRUSH–COPPER SLIP RING EXPERIMENTAL DATA

Brush	Maximum pressure 10^{-9} torr	Brush current (amps)	Composition before rot. (a/o): Cu	Composition before rot. (a/o): total impurities	Composition before rot. (a/o): C	No. of rot. (n)	Composition after rot. (a/o): Cu	Composition after rot. (a/o): total impurities	Composition after rot. (a/o): C	Contact Resist before rot. (mΩ)	Contact Resist after rot. (mΩ)	ΔR/ΔI*	Increase in brush temp. at end (°C)
1		+	42	58	44		98.3	1.7	1.0	1.21	0.47	0.013	11
	4	0.05				825							
2		-	46	54	37		97.9	2.1	1.4	1.78	1.17	0.012	--
1		-	59	41	34		96.4	3.6	2.3	2.40	0.60	0.048	9
	6	-0.05				675							
2		+	60	40	30		97.6	2.4	1.5	3.50	1.50	0.053	--
1		+	56	44	30		87.9	12.1	7.9	1.05	0.64	0.013	13
	4	5				365							
2		-	51	49	33		86.7	13.1	9.3	2.40	1.68	0.020	--
1		-	60	40	34		94.8	5.2	3.4	0.92	0.48	0.013	13
	5	-5				305							
2		+	56	44	38		94.2	5.8	3.8	1.92	1.45	0.012	--
1		+	48	52	42		97.1	2.9	2.0	1.60	0.85	0.015	24
	4	32				710							
2		-	53	47	35		95.2	4.8	3.7	1.73	1.01	0.017	--
1		-	31	69	59		91.5	8.5	3.5	1.40	0.54	0.014	17
	4	-30				400							
2		+	32	68	55		92.2	7.8	3.8	2.50	1.49	0.017	--

*ΔI represents the total change in surface impurity concentration.

Fig. 5. SEM photograph of OFHC Cu slip ring, negative track, showing topography and broken brush wire pieces *W*. Arrow gives direction of relative brush motion.

Fig. 6. SEM photograph of wear surfaces on Cu wires of brush. Arrow gives direction of motion of the slip ring across these surfaces.

reverse polarity experiments were carried out. Use of a neutral brush permitted the measurement of contact resistance for both the positive and negative interfaces. No systematic relationship between contact resistance and current density was observed. An Auger electron spectrometer was used to determine the chemical composition of the positive and negative tracks on the slip ring.

The results show that, for each experiment, the ratio of the change in resistance ΔR to the change in surface impurity concentration ΔI is approximately the same for the positive and negative brushes. Carbon was found to be the major constituent of the impurity concentration. However, for different experiments, the surface composition and contact resistances do not correlate well. This result is due to different initial conditions in different experiments, such as slightly different lead resistances, different chemical composition at the initial interface, and different contact pressures and geometries of the brush wires. These experimental variables presumeably gave rise to the parallelism of the contact resistance curves in Figs. 3 and 4. On this basis it is the *change* in contact resistance ΔR that is due to the chemical impurities at the brush-slip ring interface, the absolute values being due largely to systematic experimental variables determined by the initial conditions of the experiment.

It should also be noted that the initial interfacial impurities are distributed throughout a volume of material close to the initial interface by the mechanical "mixing" arising from the plastic deformation that occurs while the slip ring rotates in contact with the brushes. Thus an initial interfacial resistance is converted to the volume resistance of a thin layer near the original interface during the course of the experiment. The electrical resistance of this layered distribution of impurities is significantly lower than that of the initial surface distribution of the same impurities. Nevertheless, it will depend on the total number of impurities at the original interface and, of course, the number of slip ring revolutions that have occurred. Thus the curves in Figs. 3 and 4 would be expected to have small vertical displacements, after hundreds of revolutions, determined by the total surface impurity concentration at the initial interface.

It was also observed that the contact friction increased substantially as the contact surfaces became cleaner. As the

rotation proceeded the frictional forces increased until the adhesive forces on the clean portions of the interface exceeded the available torque of the motor turning the slip ring. At this point permanent welding occurred, and it caused the slip ring to stop rotating. The SEM work showed that pieces of the brush wires had broken off and became permanently welded to the slip ring. The wear surfaces themselves consisted of an extremely rough and ridged topography that had clearly undergone severe plastic deformation.

Finally, the temperature measurements indicated that during rotation the temperature near the interface rose some 10 to 25°C above room temperature, the higher values applying to the higher current densities. Apparently much higher temperatures were prevented by the high thermal conductivity of the brush and slip ring materials. Clearly, the temperature increase was not significantly related to the current density since an increase in current of more than two order of magnitude resulted in only a modest rise in temperature. These results suggest that interfacial friction, rather than current density may be the principal contributor to the temperature increase observed in the present experiments.

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APPENDIX II

CHARACTERIZATION OF COPPER SLIP RING-WIRE BRUSH ELECTRICAL CONTACTS

by

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CHARACTERIZATION OF COPPER SLIP RING-WIRE BRUSH ELECTRICAL CONTACTS

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ABSTRACT

The chemical composition and the electrical and mechanical properties of the interface between a Cu slip ring that rotates in contact with two Cu wire brushes were investigated by Auger electron spectroscopy (AES), scanning electron microscopy (SEM), contact resistance, and frictional force measurements. The experiments were carried out in an ultra high vacuum system and in an environment of 1×10^{-4} torr of wet CO_2. The contact resistance at both the positive and negative interfaces decreased with increasing number of slip ring revolutions while the frictional force increased. Under the wet 10^{-4} torr CO_2 environment the increase in frictional force was smaller than that in high vacuum, which suggests that wet CO_2 has a lubrication effect even at these relatively low pressures. In situ AES measurements showed that the composition of the slip ring surface, which was initially covered by about 50 atomic per-cent (a/o) of carbon, changed drastically during rotation. After many revolutions it approached that of a clean Cu surface (total impurities <10 a/o). The decrease in contact resistance with the number of slip ring revolutions more or less paralleled the decrease in total impurities in the high vacuum experiments. This parallelism suggests that the contact resistance is caused predominantly by the surface impurities. No systematic relationship between contact resistance and brush current density was observed. SEM observations

showed that the surface material was smeared out in the brush track areas and that the initial surface impurities were buried during rotation.

I. INTRODUCTION

The current-carrying capacity and the dynamic friction and wear properties of electrical contacts are important technological considerations which are presently not very well understood. The application of some of the tools[1-5] of surface science to these problems has brought with it an increased understanding of the complexity of the situation. The present report describes the results obtained in the application of some of these techniques to an in situ study of the interface between a rotating slip ring in contact with two wire brushes in high vacuum (10^{-10} torr) and under an environment of 1×10^{-4} torr wet CO_2. It represents the initial stage of a broader research program in which the effects of controlled gaseous environments will be determined. Preliminary results of the high vacuum work were presented at the International Vacuum Conference[6] in Cannes in 1980.

II. EXPERIMENTAL ARRANGEMENT AND METHOD OF MEASUREMENT

A stainless steel UHV system (base pressure mid 10^{-10} torr range) was used to study electrical contact phenomena associated with rotation of a copper slip ring (OFHC-99.98%Cu) in contact with two copper wire brushes (each consisting of 362, 0.005" diameter, 99.99%Cu wires) running on separate tracks[7]. The brushes were pressed against the slip ring surface by means of an insulated steel spring. They can be removed from the surface by manipulating two linear-rotary vacuum feedthrus. The slip ring is attached to a magnetically coupled rotary vacuum feedthru which is turned by an A.C. motor coupled to it by a rubber belt. The UHV system contains an Auger cylindrical mirror analyzer (CMA), a 3 KeV sputter ion gun, and a 90° magnetic sector partial pressure analyzer. Schematic arrangements of the UHV chamber, slip ring-brush assembly, CMA, sputter ion gun, mass spectrometer and linear-rotary vacuum feedthrus are shown in Figs. 1 and 2.

The wet CO_2 environment was obtained by the mechanism shown in Fig. 3. This arrangement allows for an initial evacuation of the stainless steel tubing via a liquid nitrogen trapped oil diffusion-rotary pump system attached to valve 3 and a final evacuation (with valve 3 closed) through the UHV leak valve into the ion pumped UHV system. In the latter case the gas manifold was baked until a pressure in the low 10^{-8} torr range was achieved in the UHV system. Gases dissolved in the water were flushed out first with helium (via valve 7) and then with CO_2 from the cylinder. The water/CO_2 mixture was then doubly distilled by placing successively liquid nitrogen baths around traps #1 and 2. The water/CO_2 mixture in trap 2 was then allowed to melt. Wet CO_2 was then introduced to the UHV system by running CO_2 from the cylinder through valve 4, through the doubly distilled H_2O/CO_2 solutions in trap 2, and finally through the UHV leak valve.

The surfaces of the slip ring and the wire brushes were polished smooth with emery paper (grit 600-A) and then rinsed in acetone and ethanol before being put in the vacuum system. The slip ring was electrically grounded and the contact resistances between (1) the upper brush and slip ring and (2) the lower brush and slip ring were recorded on a dual pen recorder for brush currents of 50mA, 5A, and 30A in vacuum, and 50mA and 30A under 1×10^{-4} torr wet CO_2 environment. With brushes retracted, the slip ring rotated at a speed of about 150 rpm, measured by an optical tachometer. The normal force on each brush was measured. The average frictional force was determined from the decrease in rotational speed of the slip ring by comparing it to a calibration involving known torques applied to the slip ring in a separate experiment in air. The Auger electron spectrometer used to determine the elemental surface composition of the slip ring surfaces was controlled by a Hewlett Packard 9825A desktop computer using a multi-programmer. Typical Auger traces covering a 50 to 1300 eV range were directly digitized. Computerized values of peak to peak heights and concentrations of the various elements were obtained. After each experiment was over, the slip ring and brushes were removed from the chamber so that SEM pictures could be taken of both the upper (1) and lower (2) surface tracks on the slip ring and also of the brush contact surfaces.

III. EXPERIMENTAL RESULTS

A. High Vacuum Condition

1. Contact Resistance and Friction

The contact resistance decreased with increasing number of revolutions. Also the rotational speed of the motor driving the slip ring decreased while the current to the motor increased, both as a result of increasing frictional force. Alternate welding and fracture at the interface resulted in an appreciable vibration culminating in permanent welding, which caused the motor to stop. The ratio of the frictional force to the measured average normal contact forces on both brushes gave the average coefficient of friction μ. The contact resistances for the upper (R_1) and lower (R_2) interfaces at a 5 Amps. D.C. brush current and the corrected[6] average μ are shown in Fig. 4. Similar results for the contact resistance were also obtained for 50mA and 30A brush currents. In Fig. 4 the circled points indicate the contact resistances R before the slip ring started rotating and after it stopped. It is clear that R did not depend significantly on the angular velocity of the slip ring. The lower contact resistance at the upper brush was due to the higher contact force there. It arises from the manner in which the forces on these brushes were applied[8]. In the experiment of Fig. 4 the normal brush forces needed to break electrical contact with the slip ring were 260 (upper brush) and 180 (lower brush) gms respectively. No systematic relationship between contact resistance and current density was observed. Also no effect of polarity on contact resistance was detected. In any case a possibly small influence would have been difficult to observe in the presence of the dominant effect arising from the different contact forces on the brushes.

2. AES Measurements

Elemental surface compositions of each of the brush tracks on the slip ring and the interface contact plus lead resistances for both brushes were reported earlier as a function of the number of revolutions n for a 50mA brush current[6]. Figure 5 shows a similar graph except that the current was increased in 5A steps after a certain number of revolutions. The circled points represent the values before the slip ring started rotating. In this set of experiments a different lead arrangement from that used for Fig. 4 was employed for the contact resistance measurements. The experiments in Fig. 5 included higher lead resistances. Also the normal brush contact forces were comparatively small (161 to 116 gms), leading to an increased number of revolutions prior to permanent welding. During AES measurements the brushes were retracted and the slip ring was continuously rotated. The measurements thus gave the average surface concentrations of the whole track, with only negligible loss in resolution. Peak to peak heights of all Auger signals were normalized to fractional atomic surface concentrations without making any other corrections. Nitrogen, oxygen, chlorine and sulfur were also detected in addition to the impurities shown in Fig. 5, but their concentrations decreased to less than approximately 1 a/o from initial values that were less than 8 a/o. Fig. 5 shows that the change in impurity concentration with n more or less parallels the change in contact resistance. A similar parallel was also observed in experiments in which a constant current of 50mA was used. The results suggest that the interface impurity concentration is directly related to the contact resistance. Finally no significant electromigration effects up to current densities of 654 amps/in^2 were detected.

3. Scanning Electron Microscopy

SEM pictures of the brush tracks on the slip ring showed that surface material was smeared out along the track areas. Thus the initial surface impurities appear to have been buried during rotation. Small pieces of brush wires W in Fig. 6 were seen adhering to various places on the slip ring. The ridges shown in this micrograph lie parallel to the direction of travel. Similar ridges lying parallel to the direction of relative motion can be observed on higher magnification micrographs obtained from the brush wire ends[6]. The ridges in the contact area arise from random localized welding of a wire to the slip ring during rotation resulting in tensile plastic deformation of the region near the weld area along the direction of motion, followed by eventual fracture of the weld. Continued rotation tends to smooth these areas into ridges. The micrograph in Fig. 7 shows a worn surface of the brush wire ends on the lower brush #2. The surfaces are rough and badly deformed. Small pieces of material are also seen on their leading and trailing edges.

B. Wet CO_2 (1×10^{-4} torr) Environment

Table 1 below lists the various parameters that were measured in 4 experiments in a 10^{-4} torr wet CO_2 environment. After the slip ring rotated in contact for about 5 minutes, the brushes were retracted and the wet CO_2 was pumped out. The AES spectra of the contact surfaces were then taken when a residual gas pressure in the 10^{-8} torr range was achieved after 15 to 30 minutes of pumping. A mass spectrum taken of this residual atmosphere (after the AES analysis was completed) showed water vapor as its major constituent. The initially dirty surfaces of the slip ring (Cu < 50 a/o) became much cleaner (total impurities < 10 a/o) after rotation. The surface impurities were buried in a manner similar to that in the vacuum experiments. The higher final resistances

at the lower brush interface were due to the lower normal forces there. The contact resistances for the upper (R_1) and lower (R_2) interfaces for a 50mA brush current and the coefficient of friction (μ) under 1×10^{-4} torr wet CO_2 environment are also shown in Fig. 4 (experiment #4 in Table 1), along with typical high vacuum results. The same trends are observed for both sets of experiments except that for wet CO_2: (1) the magnitude of the increase of the coefficient of friction with the number of revolutions of the slip ring was smaller than that in vacuum, (2) the sliding contact resistances reached steady state values, (3) cold welding did not take place, and (4) the contact resistances are higher than in vacuum. All of these results imply that wet CO_2 acts as a lubricant even at the relatively low pressure of 10^{-4} torr. The higher resistance when wet CO_2 is present is most likely due to the presence of water and CO_2 molecules at the interface. Subsequent scanning electron micrographs of slip ring tracks and brushes were taken and are shown in Figs. 8 and 9. Both figures show that the contact surfaces are somewhat smoother compared to the corresponding micrographs taken from the surfaces rotated in vacuum (see Fig. 6 and 7). Also broken pieces of wires were much less in evidence for the surfaces rotated in wet CO_2.

DISCUSSION

The chemical composition changes on the slip ring surface before and after rotation in contact with brushes were carefully investigated in experiments under both high vacuum and 1×10^{-4} torr wet CO_2 environments. The initial compositions depended upon the cleaning procedure and the time the slip ring was left in air before being put into the UHV chamber. In both cases the initially dirty surfaces became very much cleaner after several hundred rotations. Carbon was the major impurity observed on vacuum rotated slip ring surfaces while the concentrations of sulfur and carbon were approximately equal in the wet CO_2 case where they were the major impurities observed. The sulfur concentrations were negligible (< 1 a/o) in the vacuum experiments. They were about 5 a/o in the wet CO_2 experiments. Preliminary results suggest that the extra sulfur in the wet CO_2 case came from an impurity in the CO_2 gas and not as a result of segregation from the slip ring bulk material[9]. In particular 5 to 6 a/o of sulfur also appeared on sputter-cleaned flat 99.9999% copper samples after exposure at 25°C to wet CO_2 at atmospheric pressure.

Although the magnitude of the contact resistances differ from experiment to experiment because of inevitable differences of initial geometries, the resistance curves during slip ring rotation are much more stable in a wet CO_2 environment than in vacuum. This result is due to the lower friction and smoother rotation that resulted from the lubrication effect of wet CO_2[4,7,10-12]. The very small amounts of carbon and oxygen observed by AES on surfaces which had been rotated in wet CO_2 indicate that CO_2 was physisorbed on these surfaces, rather than chemisorbed. In the latter case high carbon and oxygen concentrations would have been expected as a result of long mean stay times of the CO_2 molecule on the surface even in vacuum. The experiments show clearly that the

opposite effect was observed. Thus physically adsorbed wet CO_2 therefore appears to form a thin loosely bound lubricating layer between the brush and slip ring surface and this layer introduces a somewhat higher contact resistance.

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TABLE I

SUMMARY OF SLIP RING-BRUSH EXPERIMENTS IN 1 x 10^{-4} torr WET CO_2

Exp #	Residual pressure 10^{-9} torr	BRUSH		Cu Composition (a/o)		Contact resistance (mΩ)		Brush normal force (gms)
		current (amps)	Brush #	before rotation	after rotation	before rotation	after rotation	
1	0.8	30	1	30	95	1.0	0.6	210
			2	20	90	2.8	2.2	163
2	1.8	30	1	35	96	1.5	0.8	194
			2	31	99	1.8	1.6	153
3	1.8	0.05	1	49	91	1.8	1.4	192
			2	36	93	1.8	1.6	137
4	0.5	0.05	1	23	92	1.8	0.6	211
			2	24	95	1.8	1.6	174

FIG. 1 TOP VIEW OF THE UHV SYSTEM AND SLIP RING-BRUSH ASSEMBLY.

FIG. 2 SCHEMATIC DIAGRAM OF THE SLIP RING-BRUSH ASSEMBLY ATTACHED TO THE MANIPULATOR INSIDE THE VACUUM CHAMBER.

FIG. 3 MECHANISM FOR THE INTRODUCTION OF WET CO_2.

FIG. 4 CONTACT RESISTANCE AND AVERAGE COEFFICIENT OF FRICTION VERSUS SLIP RING REVOLUTIONS. HIGH VACUUM (5 AMPS BRUSH CURRENT) AND 1×10^{-4} torr WET CO_2 (50mA BRUSH CURRENT).

FIG. 5 CONTACT PLUS LEAD RESISTANCE AND COMPOSITION OF BOTH SLIP RING TRACK SURFACES AS A FUNCTION OF SLIP RING REVOLUTIONS. (HIGH VACUUM CONDITION).

FIG. 6 SEM PHOTOGRAPH OF OFHC Cu SLIP RING, TRACK 2, SHOWING BROKEN WIRE PIECES W AND RIDGES. ARROW GIVES DIRECTION OF RELATIVE BRUSH MOTION. (HIGH VACUUM CONDITION).

FIG. 7 SEM PHOTOGRAPH OF THE WEAR SURFACES ON THE Cu WIRES OF BRUSH 2. ARROW GIVES THE DIRECTION OF MOTION OF THE SLIP RING. (HIGH VACUUM CONDITION).

FIG. 8 SEM PHOTOGRAPH OF OFHC Cu SLIP RING, TRACK 2, SHOWING RIDGED SURFACE. ARROW GIVES DIRECTION OF RELATIVE BRUSH MOTION. (1×10^{-4} torr WET CO_2).

FIG. 9 SEM PHOTOGRAPH OF THE WEAR SURFACES ON THE Cu WIRES OF BRUSH 2. ARROW GIVES THE DIRECTION OF MOTION OF THE SLIP RING. (1×10^{-4} torr WET CO_2).

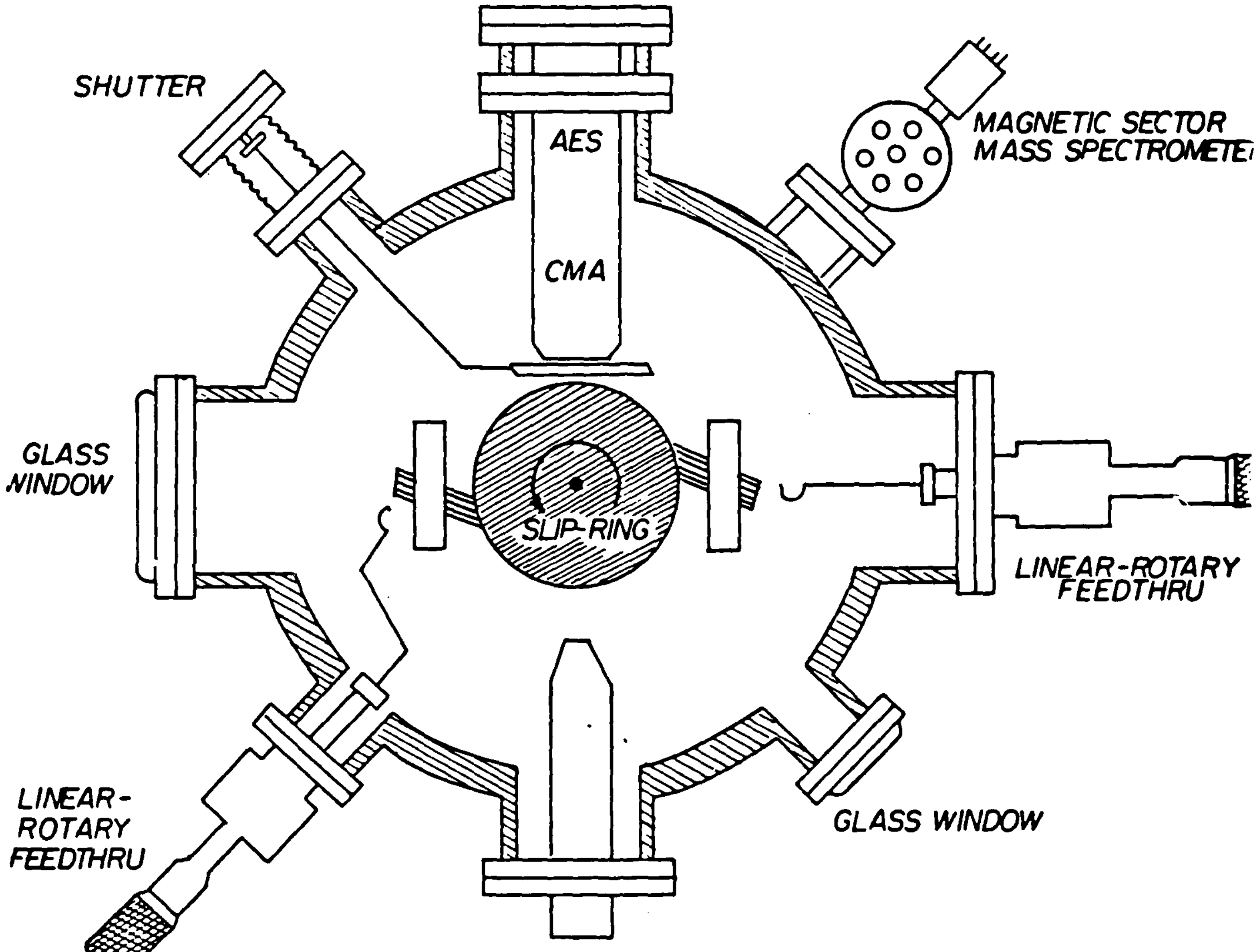

SHUTTER
AES
CMA
MAGNETIC SECTOR
MASS SPECTROMETE
GLASS
WINDOW
SLIP-RING
LINEAR-ROTARY
FEEDTHRU
LINEAR-
ROTARY
FEEDTHRU
GLASS WINDOW
SPUTTER ION GUN

Figure 1

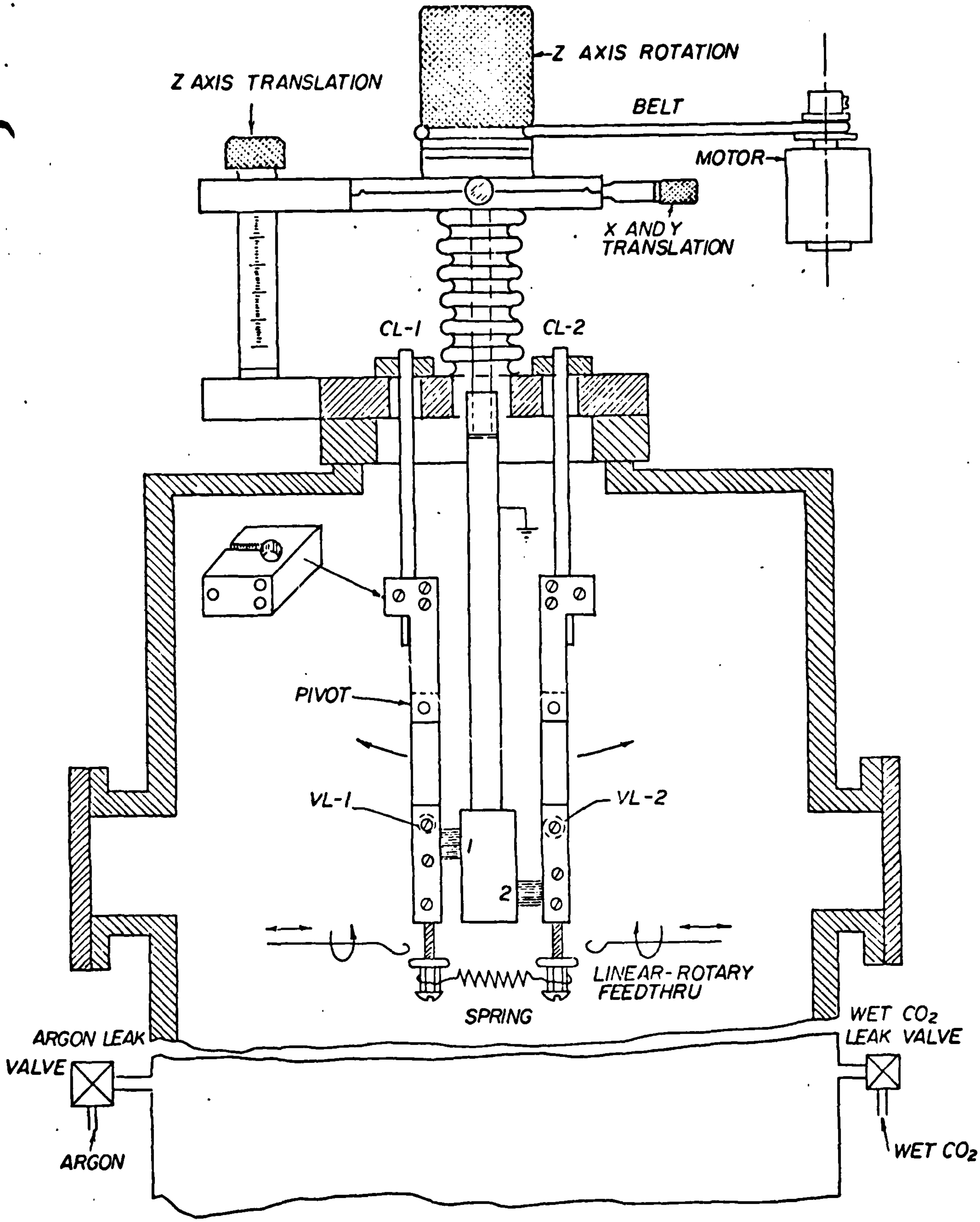

Z AXIS ROTATION
Z AXIS TRANSLATION
BELT
MOTOR
X AND Y
TRANSLATION
CL-1
CL-2
PIVOT
VL-1
VL-2
1
2
LINEAR-ROTARY
FEEDTHRU
SPRING
ARGON LEAK
VALVE
ARGON
WET CO_2
LEAK VALVE
WET CO_2

Figure 2

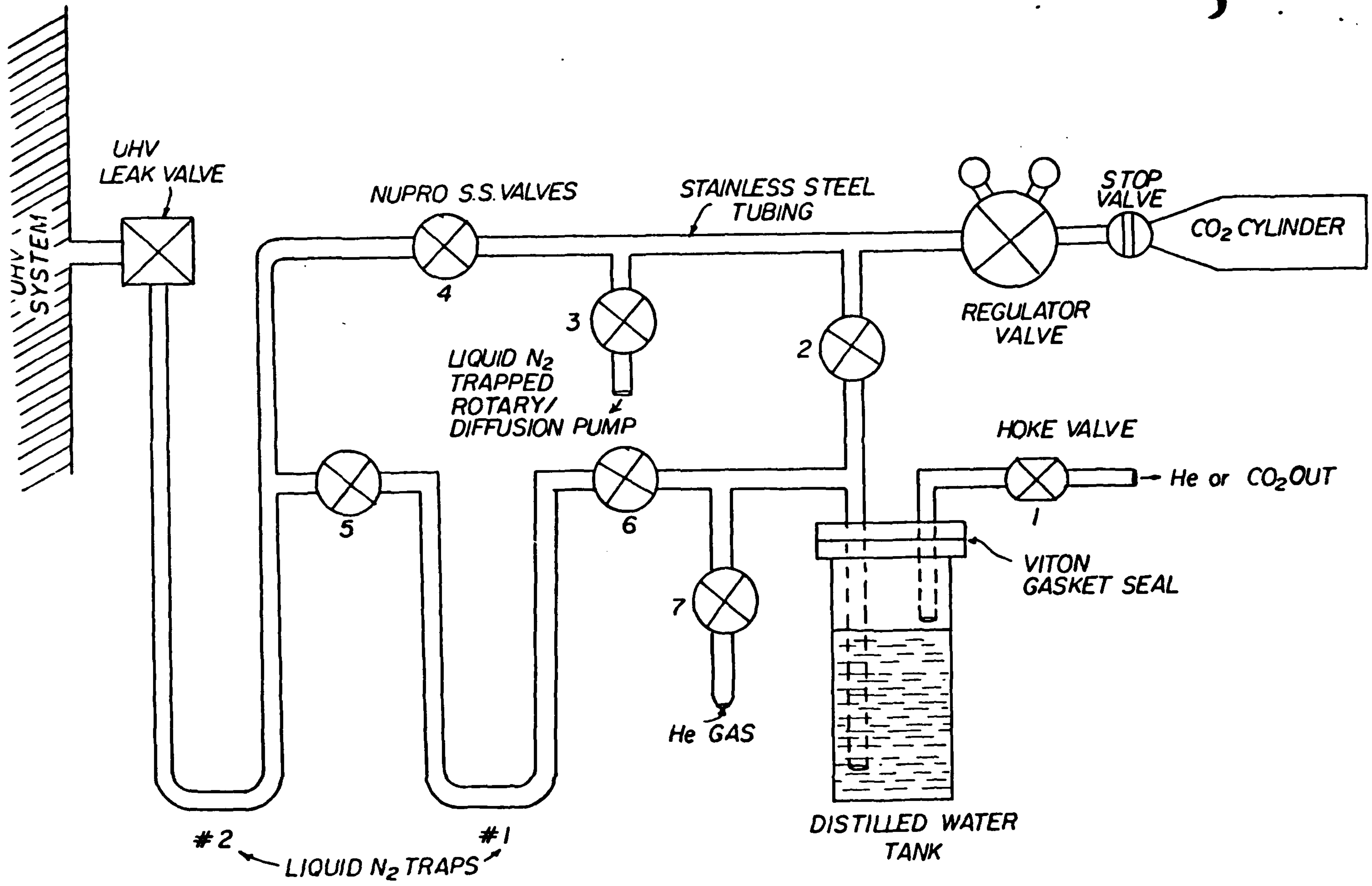
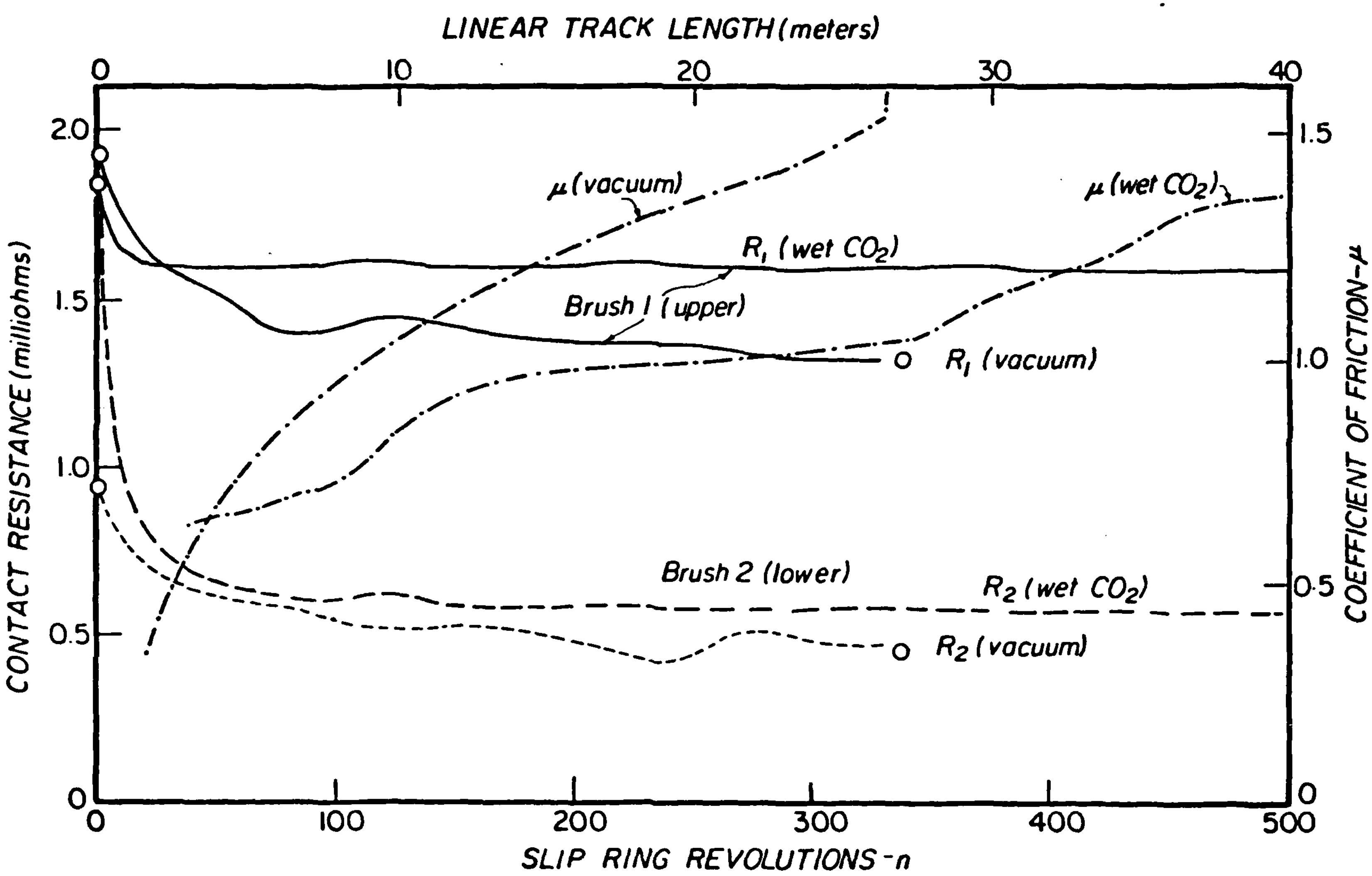
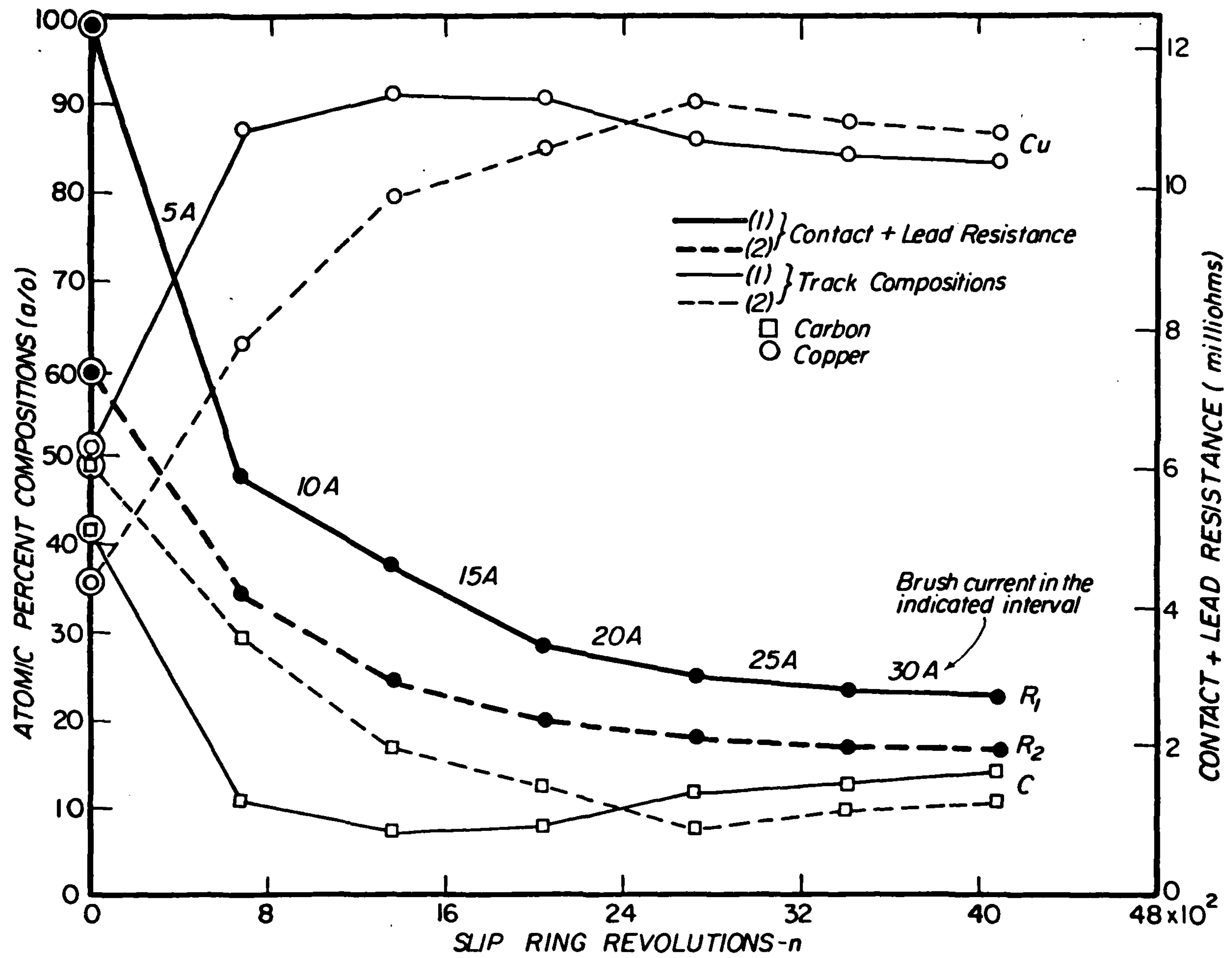

UHV SYSTEM
UHV LEAK VALVE
NUPRO S.S. VALVES
STAINLESS STEEL TUBING
STOP VALVE
CO_2 CYLINDER
REGULATOR VALVE
4
3
2
LIQUID N_2 TRAPPED ROTARY/ DIFFUSION PUMP
HOKE VALVE
He or CO_2 OUT
5
6
1
VITON GASKET SEAL
7
He GAS
DISTILLED WATER TANK
#2
#1
LIQUID N_2 TRAPS

Figure 3



LINEAR TRACK LENGTH (meters)
0
10
20
30
40
2.0
1.5
1.0
0.5
0
CONTACT RESISTANCE (milliohms)
1.5
1.0
0.5
0
COEFFICIENT OF FRICTION-μ
μ (vacuum)
μ (wet CO_2)
R_1 (wet CO_2)
Brush 1 (upper)
R_1 (vacuum)
Brush 2 (lower)
R_2 (wet CO_2)
R_2 (vacuum)
0
100
200
300
400
500
SLIP RING REVOLUTIONS-n

Figure 4



ATOMIC PERCENT COMPOSITIONS (a/o)
CONTACT + LEAD RESISTANCE (milliohms)
SLIP RING REVOLUTIONS-n
48x10^2
(1)
(2)
Contact + Lead Resistance
(1)
(2)
Track Compositions
Carbon
Copper
Cu
R1
R2
C
5A
10A
15A
20A
25A
30A
Brush current in the indicated interval

Figure 5

Figure 6

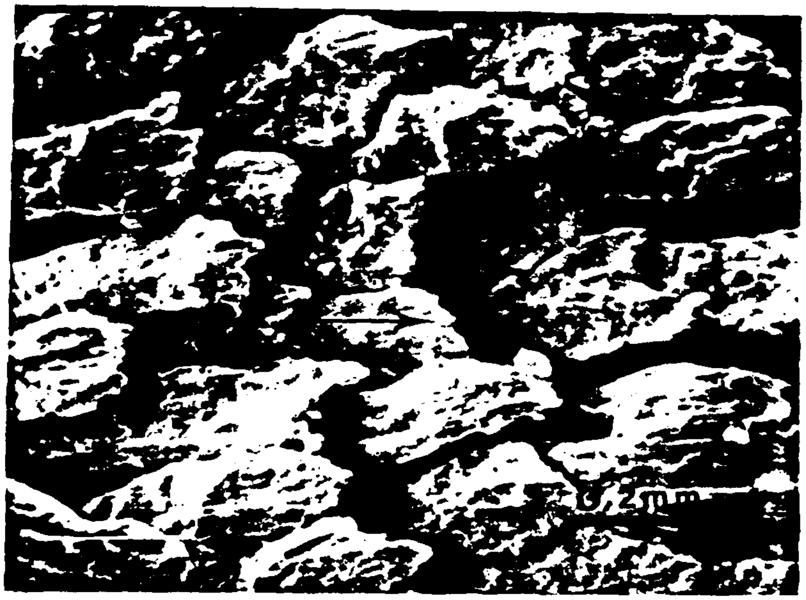


Figure 7

Figure 8

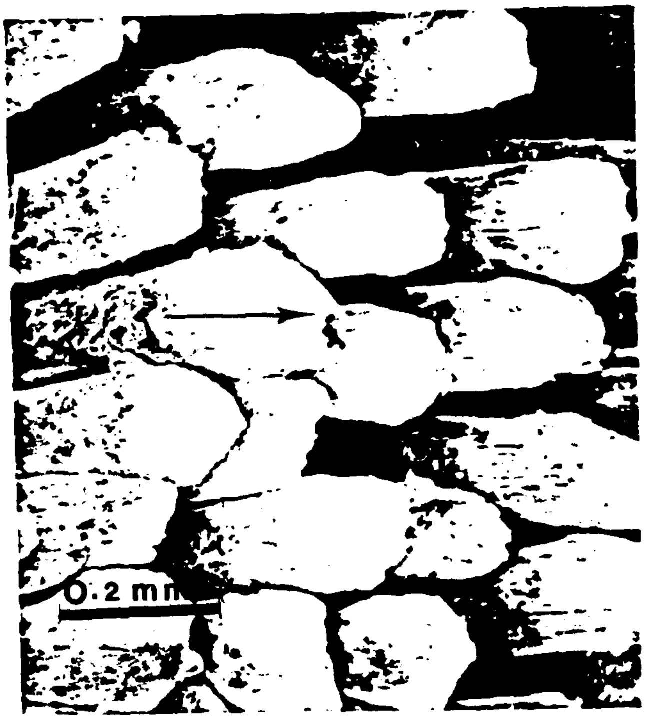


Figure 9

APPENDIX III

IN SITU AES CHARACTERIZATION OF WET CO_2 LUBRICATED SLIDING COPPER ELECTRICAL CONTACTS

by

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In Situ AES CHARACTERIZATION OF WET CO_2 LUBRICATED SLIDING COPPER ELECTRICAL CONTACTS

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ABSTRACT

The electrical contact resistance, elemental surface composition and friction of an OFHC copper slip ring rotating in contact with two high purity copper wire brushes on different tracks were investigated in situ for heavy and light contact normal forces under a wet CO_2 environment at atmospheric pressure. Scanning electron microscopy was also used to characterize the slip ring and brush surfaces. Previous work in ultra high vacuum showed that as rotation proceeded, interfacial impurities were almost totally removed, the electrical contact resistance decreased, and the friction increased until cold welding occurred. In the present work, the slip ring surface was sputter cleaned (Cu >95%) before contact rotation and was only slightly contaminated after rotating in wet CO_2. Both the contact resistance and friction decreased quickly and reached steady state values almost simultaneously in the early stages of rotation. Also cold welding phenomena did not occur. Scanning electron micrогrpahs taken after each experiment showed that the surfaces of the slip ring tracks and the brush wire ends were much rougher when heavy contact normal forces were used than in the light normal force condition. All of these results confirm that wet CO_2 is an effective lubricant for Cu to Cu electrical sliding contacts.

INTRODUCTION

Most previous studies of electrical contact phenomena have been carried out under normal atmospheric conditions. Recently, however, it has been found that the electrical and mechanical properties of rotating electrical contacts can be strongly influenced by the gaseous environment in which they operate.[1-3] One particularly auspicious environment is wet CO_2 at atmospheric pressure. Not only does it give rise to low values of friction and wear, but it also permits the flow of high currents across the interface.[4] In the present work this environment was used in a study of the interface between a Cu wire brush and a rotating Cu slip ring across which a high current flowed. The elemental composition of the surface of the slip ring was measured in situ with Auger electron spectroscopy (AES) as a function of exposure and the number of rotations in contact with the brush. Similarly measurements of electrical contact resistance and friction were made. The surfaces of both the brushes and slip ring were examined subsequently by scanning electron microscopy (SEM). Both high and low normal contact forces were used in the experiments. The results were different from those carried out earlier under ultra high vacuum (UHV) conditions in several significant ways.[5]

EXPERIMENTAL DETAILS

Figure 1 shows a block diagram of the complete experimental system. A stainless steel UHV system was used to investigate electrical contact phenomena associated with rotation of a copper slip ring in contact with two copper wire brushes running on different tracks. Residual pressures in the low 10^{-9} torr range were obtained in the baked system. The brushes are pressed against the slip ring by means of an electrically insulated stainless steel spring. They can be removed from contacting the slip ring surface by manipulating two linear-rotary vacuum feedthrus. The slip ring is axially attached to a magnetically coupled rotary feedthru which is turned by an A.C. motor coupled to it by a rubber belt. The slip ring is a 1" diameter cylinder of OFHC (99.98%) Cu and the brushes each consist of 362, 0.005" diameter, 99.999% Cu wires. The whole brush-slip ring assembly is mounted on a specimen manipulator capable of x, y, z displacements. The UHV system also contains an Auger cylindrical mirror analyzer (CMA), a 3 Kev sputter ion gun and a 90^0 magnetic sector partial pressure analyzer. The details of the slip ring-brushes assembly, UHV system, and AES measurements were given previously.[5-7]

The surfaces of the slip ring and wire brushes were polished smooth with emery paper (grit 600-A), rinsed in acetone and ethanol, and then cleaned in an ultrasonic bath for 30 min. before being put in the vacuum system. After the system was baked and pumped to 5×10^{-9} torr pressure, Auger spectra were taken from the contaminated slip ring surface (Cu < 50%). Then argon was introduced into the vacuum chamber through the leak valve to a pressure of $1 - 2 \times 10^{-5}$ torr and the slip ring surface was sputter cleaned for 2.5 hrs. with a primary electron beam setting of 3000 volts and 30 mA. Subsequent AES measurements showed that the slip ring surface was almost

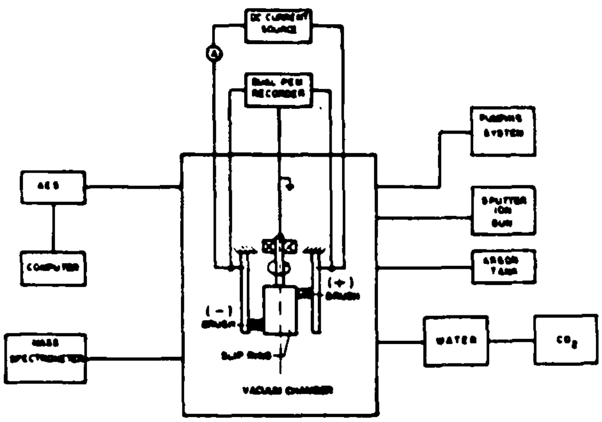

FIG. 1. Block diagram of UHV system and attachments for the electrical sliding contact experiments.

completely cleaned (Cu > 99% in the center region of the bombarding ion beam).

Wet CO_2 at atmospheric pressure was obtained by allowing the gas to flow through a distilled water trap and then into the vacuum chamber via a vacuum leak valve. The detailed procedures will be reported elsewhere.[8] The rotating electric contact experiment was then performed with 30 amps current running through the contact interfaces. An angular velocity of $\sim$ 150 rpm was used. During the experiment, the slip ring was electrically grounded by means of thick copper wires sliding on the stainless steel axis, the neutral contact. The contact resistances between (1) the lower brush and slip ring and (2) the upper brush and slip ring were recorded on a dual pen recorder. The rotational speed of the slip ring was measured with an optical tachometer along with the input power to the motor. The frictional force was determined from the calibrated decrease in rotational speed of the slip ring.[9] Then the ratio of the frictional force to the sum of the measured normal contact forces on both brushes gave the coefficient of friction μ.

After 10 minutes of rotation, the brushes were retracted and the wet CO_2 was pumped out. AES spectra of the contact surfaces were taken when a residual gas pressure in the 10^{-8} torr range was achieved after at least 30 hrs. of pumping. Subsequent sputtering and AES spectra were taken alternately at regular intervals to get the concentration depth profiles of the elements on the slip ring surface. After the experiment was over, the slip ring and brushes were removed from the vacuum chamber. SEM pictures were taken of both the lower and upper surface tracks and also of the brush contact surfaces.

RESULTS

A. Contact Resistance and Friction Measurements

The coefficients of friction and the electrical contact resistances of both the lower and upper interfaces for two different experiments are shown in Fig. 2. Both were carried out under similar conditions except for different contact forces. During rotation a direct current of 30 amperes (approximately 4200 A/in^2) ran through the contacts. The subscripts s, w, u, ℓ in Fig. 2 denote strong spring, weak spring, upper interface and lower interface respectively, e.g. $R_{w\ell}$ (27g) denotes the electrical resistance of the lower interface in the weak spring experiment. 27g is the corresponding contact normal force. Contrary to the corresponding experiments carried out in UHV,[9] the coefficients of friction in the present experiments decreased with increasing number of slip ring revolutions until steady state values were obtained. Although the electrical contact resistances of the lower and upper interfaces in the present experiments decreased with increasing number of slip ring revolutions, as in the UHV experiments, they reached their steady state values more rapidly and remained stable without adhesion in the former case. This stability and lack of cold welding demonstrated the lubricating function of wet CO_2. In addition the resistance curves were more or less parallel to each other, indicating that the initial conditions determined whether a curve was "low" or "high". These initial conditions include such variables as brush orientation, stiffness, and contact force. In the latter case a higher contact force always resulted in a lower contact resistance, as expected.

B. Auger Electron Spectroscopy

The elemental compositions of the lower track (track one), upper track (track two) and neutral track (track zero, which is between tracks one and two) of the slip ring surface before sputtering, after sputtering and after running in wet CO_2 for the strong and weak spring experiments are listed in Table 1. The elemental balances in

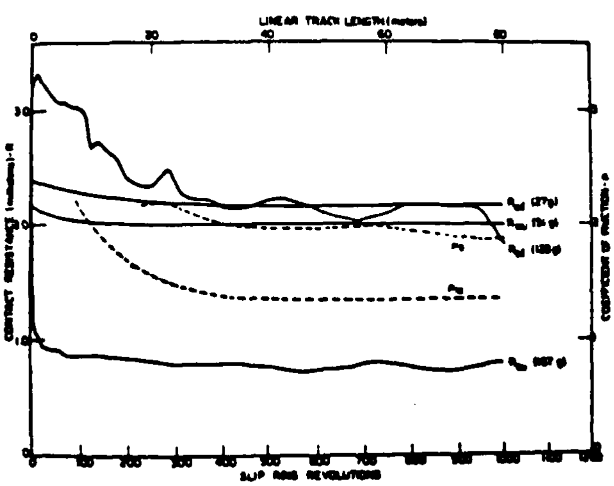

FIG. 2. Electrical contact resistances and coefficients of friction vs. number of slip ring revolutions under one atmosphere of wet CO_2 and 30 amps brush current (4.2 KA/in^2 or 654 amps/cm^2). Notations - see text.

Table 1 Elemental Compositions of Slip Ring Tracks Before Sputtering, After Sputtering and After Rotating in Wet CO_2 (and 30 hrs of pumping) for the Strong and Weak Spring Experiments

		Concentration on slip ring (± 0.1 a/o)					
		Strong Spring			Weak Spring		
	Track	Before Sputtering	After Sputtering	After Rotating in wet CO_2	Before Sputtering	After Sputtering	After Rotating in wet CO_2
Cu	1	48.4	83.6	93.3	39.9	99.4	88.0
	0	29.8	95.8	91.8	45.7	99.1	89.3
	2	16.9	99.0	93.3	49.8	99.7	88.8
S	1	0.0	0.1	4.5	0.0	0.0	4.7
	0	0.0	0.1	3.2	0.0	0.2	5.0
	2	0.0	0.1	4.8	0.0	0.0	5.2
C	1	35.3	12.9	2.2	40.9	0.6	7.3
	0	59.7	3.6	4.7	39.3	0.5	5.5
	2	68.9	0.6	1.6	35.1	0.2	5.6
O	1	15.6	3.3	0.0	14.2	0.0	0.0
	0	10.4	0.3	0.2	12.9	0.0	0.1
	2	14.2	0.2	0.1	11.4	0.1	0.2
Balance	1	0.7	0.1	0.0	5.0	0.0	0.0
	0	0.1	0.2	0.1	2.1	0.2	0.1
	2	0.0	0.1	0.2	3.7	0.0	0.2

Table 1 mainly consisted of chlorine and nitrogen. The slip ring surfaces for both experiments were initially largely covered by impurities. With the ion sputter gun aimed at the neutral track region, i.e. between tracks 1 and 2, very clean surfaces were obtained for all three tracks in the weak spring experiment. In the strong spring experiment similar cleaning effects were observed after sputtering, but somewhat more impurities remained on track 1 and the neutral track regions because the ion gun had been aimed at track 2 instead.

After running in wet CO_2, the slip ring surfaces became contaminated only slightly (see Table 1). The major contaminants were carbon and sulfur. Notice also that the contamination in the near surface region is less serious in the strong than in the weak spring experiment. Figures 3 and 4 show the elemental depth profiles of sulfur and carbon on the slip ring after running in one atmosphere of wet CO_2. The order of taking AES was track 2, neutral and track 1. The impurities on the neutral track generally were more easily sputtered away because they were only adsorbed on the surface of the slip ring. The impurities on tracks 1 and 2, however, took a longer time to be sputtered away because they were buried in the near surface region of the copper substrate by the mechanical mixing action of the brushes. For example in Fig. 4, it took four times as long for the carbon concentration to reach the initial (or "background") level in the case of track 2 than for the neutral track. Note also from Table 1 and Figs. 3 and 4 that the mechanical mixing of impurities in the near surface region by the brushes is more significant when there are light loads on the brushes.

A separate experiment was done to examine the high concentration of sulfur on the slip ring surface after rotating in wet CO_2. A very pure flat copper specimen (99.9999%) was cleaned and mounted on the manipulator in the UHV chamber. The system was evacuated and the Cu specimen cleaned by sputter ion etching. It was then exposed to one atmosphere of wet CO_2, which was then pumped out. Although all measurements and experimental processes took place at room temperature without any mechanical disturbance of the surface, the sulfur concentration on the flat specimen surface was found to be about the same (~ 5 a/o) as that of the slip ring surface after rotating in contact with two brushes in one atmosphere of wet CO_2. See Table 1. Clearly, the extra amount of sulfur on the surfaces of both the flat specimen and the slip ring came from an impurity in the CO_2 gas and not as a result of segregation from the bulk of the Cu sample.[7]

C. Scanning Electron Microscopy

SEM pictures of slip ring tracks and brush wire ends for both the strong and weak spring experiments were taken after the experiments were over and the manipulator was taken out of the vacuum chamber. Figures 5 and 6 show the brush wire ends after each experiment. Clearly the contact surface of the brush wire end in the weak spring experiment is much smoother than that in the strong spring experiment. The rough region of the brush wire in Fig. 6 was produced by the initial emery paper polishing prior to insertion in the UHV chamber. It apparently did not touch

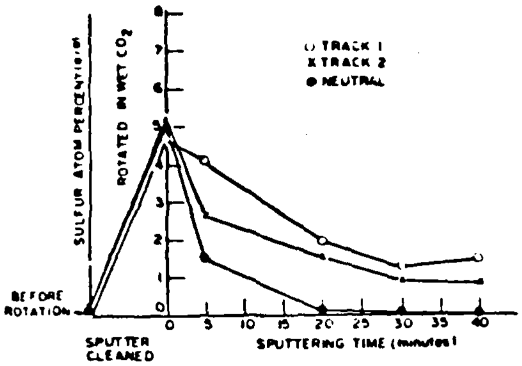

FIG. 3. Sulfur concentration depth profile on slip ring surface after rotating in wet CO_2 (weak spring condition).

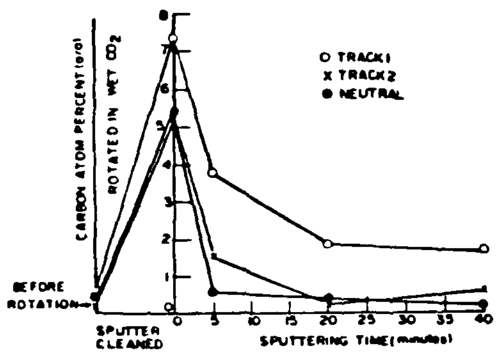

FIG. 4. Carbon concentration depth profile on slip ring surface after rotating in wet CO_2 (weak spring condition).

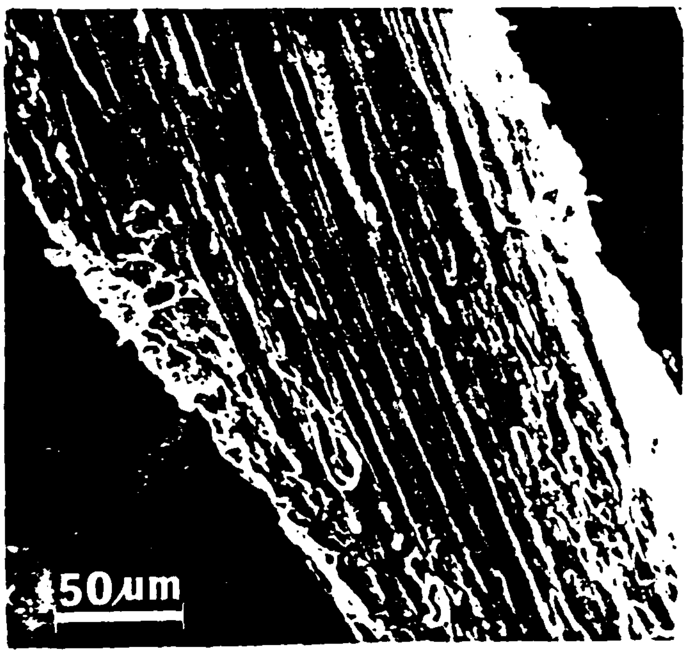

FIG. 5. SEM of a single brush wire end after sliding contact in wet CO_2 (strong spring condition, lower brush-negative).

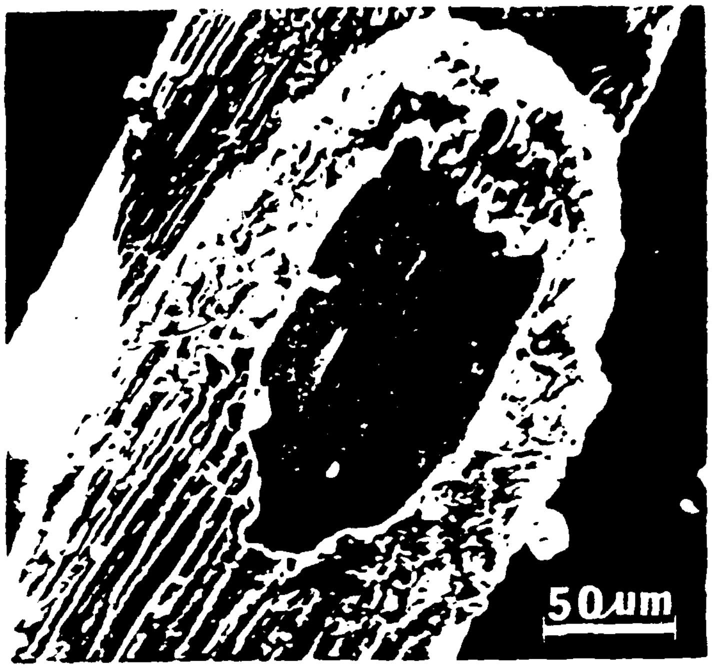

FIG. 6. SEM of a single brush wire end after sliding contact in wet CO_2 (weak spring condition, upper brush-positive).

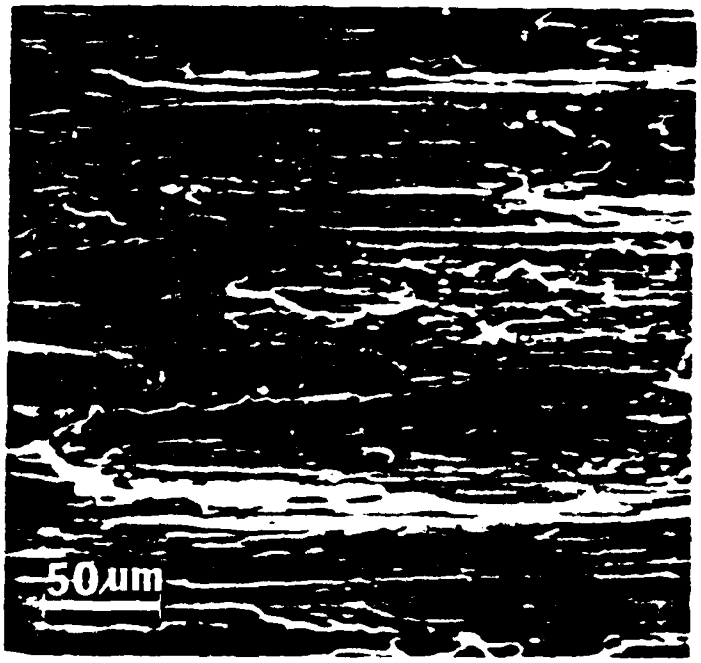

FIG. 7. SEM of slip ring track after sliding contact in wet CO_2 (strong spring condition, lower track).

the slip ring during rotation. On the other hand, the brush wire end in Fig. 5 shows a smoother surface and longer ridges compared to the rough region in Fig. 6. This surface resulted from frictional contact during rotation. Figures 7 and 8 show SEM pictures of slip ring tracks after the strong and weak spring experiments respectively. Obviously the sizes of the ridges in the surface of the slip ring track are much smaller in the weak than in the strong spring experiment. These results dramatically show that the contact normal force plays an important role in determining the

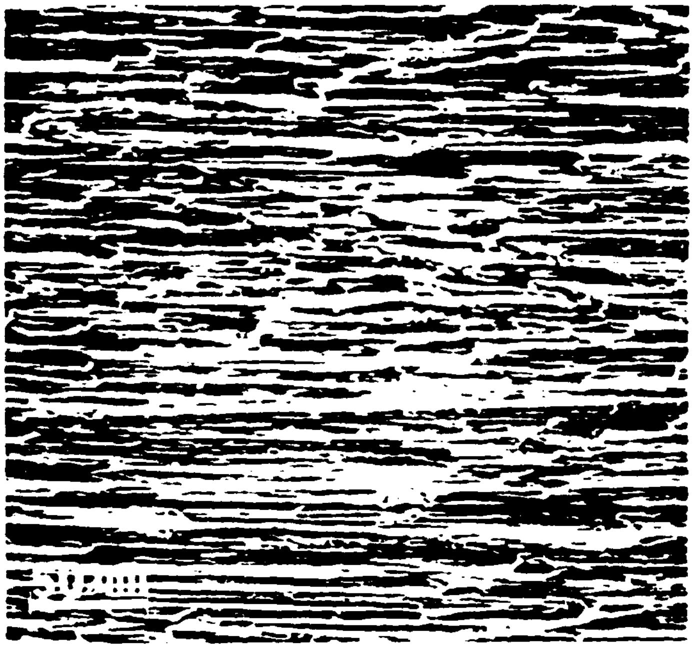

FIG. 8. SEM of slip ring track after sliding contact in wet CO_2 (weak spring, lower track).

properties of a rotating electrical contact: the *smaller the contact normal force, the lower the* contact frictional force and consequently the smoother the contact interface.

DISCUSSION

In these experiments an initially clean copper slip ring rotated in electrical and mechanical contact with two copper wire brushes through which a current of approximately 4200 A/in^2 flowed. Rotations were made in a UHV system that had been back filled with wet CO_2 at 1 atm pressure. Both strong and weak normal forces were applied to the brushes in successive experiments. The results show that except for a slight S contamination, rotation in wet CO_2 does not contaminate the surface of the slip ring. Since the surface remained essentially clean, the lubricity of the thin film at the interface must be due only to the H_2O and CO_2 molecules that are present.

In previous experiments carried out in UHV[5,7] it was shown that the interface became much cleaner as the copper brush rotated over the copper slip ring. The present results in wet CO_2 are consistent with the earlier result. In addition it was found that weak contact forces resulted in greater near surface bulk mixing of surface contaminants than stronger springs. This interpretation follows from the Auger depth profile studies. One can conclude that the greater penetration of the brush asperities into the bulk of the slip ring in the case of a stronger normal force is less effective in distributing the contaminants in the near surface region.

It was also found that the adsorbates during rotation were pumped off in less than 30 hours. This result means that they were not very tightly bound to the copper surfaces. We could not examine the surfaces by AES in a much shorter time because of the high residual gas pressure in the vacuum system. These results are consistent with the known desorption energies of water on metal surfaces, which range from 22-24 kcal/mole.[10] Since the adsorption energy of CO_2 is much less than that of H_2O, it is expected that the H_2O molecule aids in the adsorption of CO_2 during rotation.

The decreases in electrical contact resistance and friction during rotation presumeably arise from an increase in the contact area as the asperitics on the contacting faces are smoothened. This effect is most noticeable in the weak spring case where the normal forces were in the neighborhood of 30 to 50 g. Because cold welding did not occur in the wet CO_2 case, as was observed in UHV, the H_2O-CO_2 molecules must form a more or less continuous layer at the slip ring - brush interface. If this layer were broken, localized cold welding would occur. Presumeably, the higher friction in the case of higher normal forces arises from the partial fracture of this H_2O-CO_2 layer. One also expects that on the basis of this model, the thickness of the H_2O-CO_2 interfacial layer would depend on the contact pressure. The electrical contact resistance measurements support this view. In all cases the higher normal force has the lower contact resistance. It is expected that the interfacial resistance arises from a combination of quantum mechanical tunneling through the CO_2-H_2O layer as well as occasional, erratic direct brush-slip ring cold welding, resulting in fracture of surface regions from the bulk and concomitant wear. It is therefore clear from these studies that the film resistance at a Cu-Cu interface is not due to contamination by carbon, organic impurities, etc. but rather arises from the presence of this thin H_2O-CO_2 layer at the interface.

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APPENDIX IV

MICROSTRUCTURAL CHARACTERIZATION OF ROTATING Cu-Cu ELECTRICAL CONTACTS IN VACUUM AND WET CO_2 ENVIRONMENTS

by

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MICROSTRUCTURAL CHARACTERIZATION OF ROTATING Cu-Cu ELECTRICAL CONTACTS IN VACUUM AND WET CO_2 ENVIRONMENTS

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ABSTRACT

The chemical, electrical and wear properties of the rotating interface between OFHC Cu slip rings and two high purity Cu wire brushes were investigated in situ in ultra high vacuum and in one atmosphere wet CO_2. The chemical composition of the slip ring surface was determined by Auger electron spectroscopy (AES). The contact resistance was measured by a potentiometric four point probe technique while the wear properties of the interface and the morphology of the debris were studied by frictional force, SEM, TED and XRD measurements. Rotation in UHV of a conventionally cleaned (CC) slip ring produced a much cleaner surface. The contact resistance of both brush interfaces decreased and the frictional force increased with increasing number of revolutions. After many revolutions the brush and slip ring welded. The decrease in contact resistance with the number of slip ring revolutions more or less paralleled the decrease in total impurities. Rotation in wet CO_2 of CC slip ring and brushes also produced much cleaner surfaces. On the other hand initially argon ion sputter cleaned surfaces (SP) became slightly contaminated (mainly C and S) when rotated. The contact resistance at both interfaces and the coefficient of friction decreased with increasing number of slip ring revolutions, finally reaching steady state values.

After each experiment, SEM examination of vacuum rotated surfaces showed deep ridges and broken pieces of material on the slip ring surface and badly deformed brush wire ends. Wet CO_2 rotated surfaces were relatively smooth and shallow ridges were seen. SEM examination of wear particles collected during rotation indicated that they may have come from both the slip ring and brush wire materials and were rolled in the regions between the brush and slip ring. X-ray and transmission electron diffraction from individual particles showed a randomly oriented polycrystalline microstructure. The particles collected from the wet CO_2 experiments were much smaller in size than those collected in vacuum experiments. In wet CO_2, the contact resistance was interpreted as being predominantly due to an electron tunneling mechanism through the CO_2-H_2O molecular layer at the interface. As expected the thickness of the layer appeared to vary with the contact pressure. Friction would then arise largely when the molecular layer was occasionally broken, allowing intimate contact and temporary welding of the brush and slip ring surfaces. Subsequent fracture of these welds during continued rotation would initiate the formation of wear particles.

INTRODUCTION

Over the last twenty years considerable effort has been made theoretically (1,2) and experimentally (3,4,5) to reduce friction, wear and contact resistance between dynamic interfaces. Attempts have hitherto been made to devise conditions to yield minimum contact resistance and minimum friction and wear between the brushes and slip ring. The brush and slip ring materials and the contact load and environment are the most influential parameters affecting these properties. There are various techniques and surface tools available for the study of the atomic nature of the wear surfaces (6). In this paper Cu-Cu dynamic contact interfaces are characterized in vacuum and in one atmosphere of wet CO_2 by measuring contact resistance, frictional force, chemical composition and mechanical wear. A morphological and microstructural study of the debris formed during sliding contact provided important information about their origins and evolution. While there are various techniques (7,8) available for a morphological analysis of the wear debris, the techniques of scanning electron microscopy (SEM), X-ray diffraction (XRD), and transmission electron diffraction (TED) were used in the present study.

SLIP RING-BRUSH ARRANGEMENT AND EXPERIMENTAL PROCEDURE

The brush-slip ring arrangement has already

been described in greater detail elsewhere (9,10). A stainless steel ultra high vacuum system of low 10^{-10} torr range capability was used to characterize rotating electrical contacts. Figure 1 shows the arrangement of the Cu slip ring which

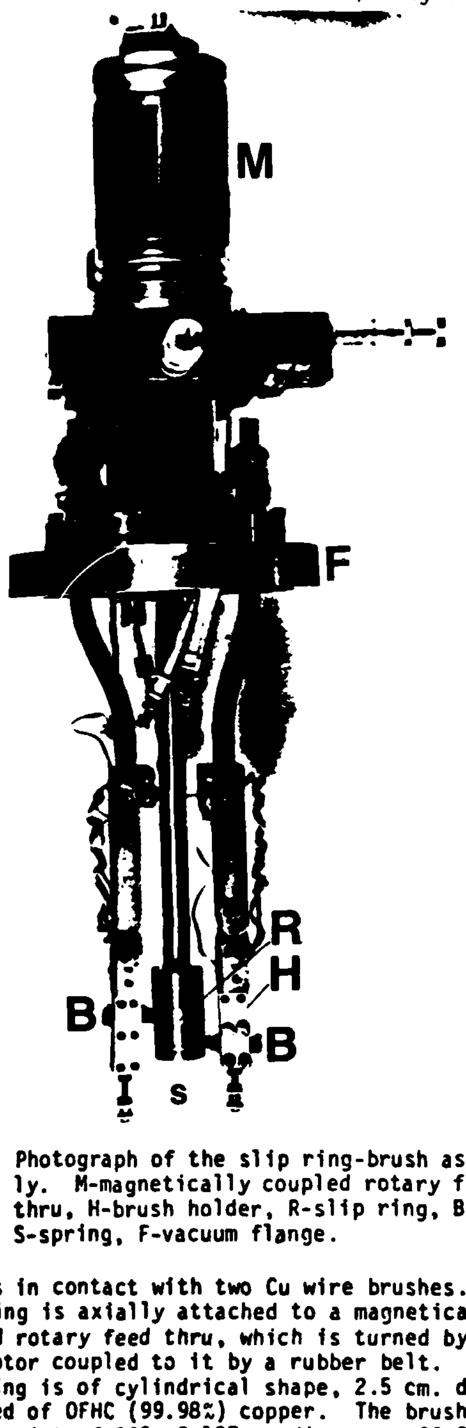

Fig. 1 Photograph of the slip ring-brush assembly. M-magnetically coupled rotary feed-thru, H-brush holder, R-slip ring, B-brush, S-spring, F-vacuum flange.

rotates in contact with two Cu wire brushes. The slip ring is axially attached to a magnetically coupled rotary feed thru, which is turned by an A.C. motor coupled to it by a rubber belt. The slip ring is of cylindrical shape, 2.5 cm. dia., composed of OFHC (99.98%) copper. The brushes each consist of 362, 0.127 mm diameter, 99.999% Cu wires. The brushes are clamped to two rectangularly shaped stainless steel electrodes, each having a smooth hinge in the middle. The brushes are arranged at 180° to each other, making an approximately 40-45° angle with the normal to the slip ring surface and axially displaced (1 to 1.5 cm) to make separate tracks on the slip ring. The whole brush-slip ring assembly is mounted on a specimen manipulator capable of X,Y,Z displacements. The UHV system includes an Auger cylindrical mirror analyzer (CMA), a 3KeV sputter ion gun and a 90° magnetic sector partial pressure analyzer.

Before each experiment, the surfaces of the slip ring and the brush wire ends were mechanically polished with a series of emery papers ending with grit 600A and then rinsed ultrasonically (brush retracted) in acetone and ethanol. The contact resistances between the two brushes and slip ring (grounded) were recorded on a dual pen recorder. Experiments were performed with three brush direct currents: 50mA, 5A, 30A in vacuum and with 30A in wet CO_2. With the brushes retracted, the speed of the rotating slip ring was monitored by an optical tachometer. During the experiment, the rotational speed of the slip ring was measured at regular time intervals along with the input power to the motor.

The Auger electron spectrometer which was used to examine the surface tracks was fully controlled by a Hewlett Packard 9825A desktop computer and multi-programmer. Typical Auger traces covering a 50 to 1300 eV range were directly digitized with an energy increment of 0.65 eV or less. Computerized values of peak to peak heights of the AES signals of various elements were obtained with a precision of 1 in 2000. These Auger spectra were taken using a primary beam energy of 3KeV, a modulation amplitude of 1 volt (peak to peak) and a 25μA beam current.

A wet CO_2 environment in the vacuum system was obtained by running CO_2 from the cylinders (commercial grade, 99.8%) through a doubly distilled H_2O/CO_2 solution in a stainless steel trap and finally through a UHV leak valve (11). The pressure of wet CO_2 in the vacuum system during the course of the rotation experiments was approximately atmospheric. Auger spectra from the wet CO_2 rotated slip ring surface were taken only after the wet CO_2 was pumped down to the high 10^{-8} torr region, a process which took about 2 days. A molybdenum sheet tray was placed inside the vacuum chamber under the brush-slip ring assembly to collect wear particles during contact rotation.

After the experiment was over, the slip ring assembly and wear debris were removed from the chamber. The normal force on each brush was measured. The average frictional force was determined from the decrease in rotational speed of the slip ring by comparing it to a calibration involving known torques applied to the slip ring in a separate experiment in air. SEM pictures were taken of both the slip ring surface tracks, brush contact surfaces and of wear particles. X-ray diffraction was obtained from relatively large particles (≈0.05mm) and transmission electron diffraction was taken from small particles (≈0.05mm or less).

RESULTS

A. Contact resistance and friction measurements.

Figure 2 shows the contact resistance for both the upper and lower interfaces and the average coefficient of friction as a function of the number of slip ring rotations or linear track

length covered. The contact resistance decreased with increasing number of slip ring revolutions. The curves are more or less parallel to each other indicating that the initial conditions determine whether a curve is "high" or "low". These initial conditions include such variables as contact force, lead resistance, brush wire orientation with respect to slip ring, surface impurities, etc. The contact resistances in the wet CO_2 experiments are consistently higher than those in the vacuum experiments and result in much smoother curves. This high contact resistance could be due to the lower normal force, smaller contact area and the additional resistance introduced by the thin wet CO_2 layer at the interface. The circled points indicate the contact resistance before the slip ring started rotating and after it stopped. In the case of wet CO_2, the slip ring rotation did not stop, but the experiment was terminated after about 5 to 10 minutes of rotation when the resistance attained steady state values. The resistance of the interfaces clearly depended on the magnitude of the contact force. In vacuum experiments, the frictional force increased substantially as the rotation proceeded and finally after many hundreds of revolutions the motor stopped rotating because of excessive friction and ultimate cold welding. The average coefficient of friction (μ) was calculated from the ratio of the frictional force to the measured normal force and is shown in Fig. 2 for

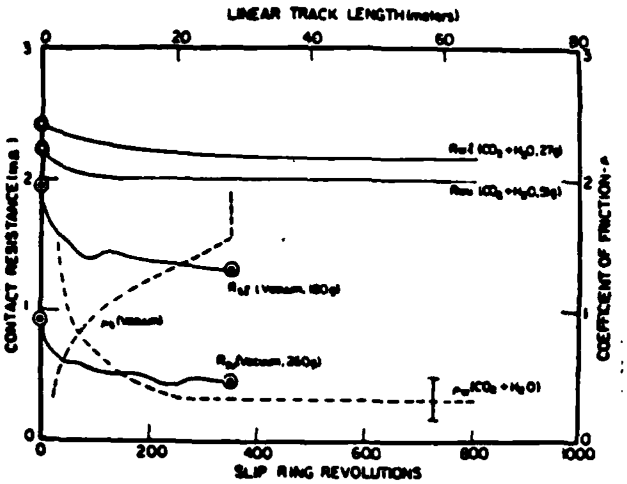

Fig. 2 Contact resistance and average coefficient of friction versus slip ring revolutions. Subscripts s, w, u and ℓ stand for strong and weak springs, and for upper and lower brush interfaces respectively.

both the vacuum and wet CO_2 experiments. For the vacuum experiment it increased more than four times while for wet CO_2 it decreased to about 0.35 where it remained relatively stable.

B. AES measurements

In the vacuum experiments, the elemental surface compositions of both the upper and lower tracks on the slip ring were obtained by AES before and immediately after the contact resistance measurements. However, in the wet CO_2 experiments Auger spectra were taken about 2 days after the contact rotation because the system had to be pumped down to the high 10^{-8} torr region before operating the Auger spectrometer. The brushes were retracted during the AES measurements and the slip ring was continuously rotated. This procedure gave the average impurity concentrations on the whole track. The peak to peak heights of all Auger signals were normalized (12,13) to atomic percent (a/o) concentrations. The elemental surface concentrations on the slip ring for two typical experiments in vacuum and wet CO_2 are given in Table I. The Cu, S, C and O concentrations are

TABLE I

Elemental concentrations (a/o) on slip ring tracks for rotation in vacuum (235g contact force) and wet CO_2 (51g contact force)

Elements	VACUUM Before Rotation	VACUUM After Rotation	WET CO_2 Before Sputtering	WET CO_2 After Sputtering	WET CO_2 After Rotation
Cu	47.5	97.1	39.9	99.4	88.0
S	0.8	0.1	0.0	0.0	4.7
C	42.1	2.0	40.9	0.6	7.3
O	7.1	0.4	14.2	0.0	0.0
Balance (Cl,N,Ar)	2.5	0.4	5.0	0.0	0.0

listed along with the impurity balance. In vacuum rotated experiments the CC interface became cleaner, while in the wet CO_2 experiments the sputter cleaned interface became only slightly contaminated. The impurities picked up were sulfur and carbon. Argon ion sputter depth profiles performed on the slip ring surface showed that these impurities were rapidly removed by small amounts of ion etching.

To understand the cause of the high concentration of sulfur, an additional experiment was performed in which the brush-slip ring assembly was replaced by a flat OFHC Cu sample. The sample was first sputtered clean (to 98 a/o Cu, 0.2 a/o S) and then heated to 585°C for 30 minutes where 9 a/o of sulfur segregation was detected (14). Sulfur was removed by argon ion sputter depth profiling techniques and its concentration was monitored as a function of sputtering time. After it was almost completely removed (0.2 a/o), the clean sample was exposed to one atm. of wet CO_2, resulting in a surface concentration of 7 a/o of sulfur. The sulfur concentration was again removed by

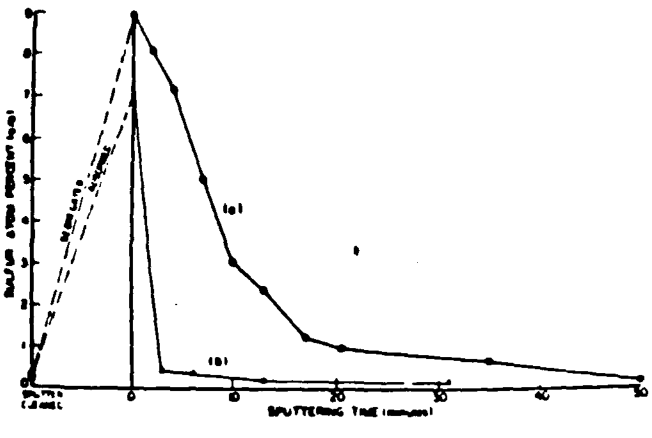

Fig. 3 Sputter depth profile of sulfur on a flat OFHC copper sample. (a) segregated on heating at 585°C for 30 mins. (b) adsorbed on exposure to one atmosphere wet CO_2 at room temperature for 15 mins.

sputter depth profiling. The results are shown in Fig. 3. It is clear that the adsorbed sulfur is removed much faster than the bulk segregated sulfur. Thus the high concentration of sulfur on the slip ring surface was due to an impurity in the wet CO_2 supply and not to bulk segregation.

C. Scanning Electron Microscopy

After each experiment, the brush-slip ring assembly and wear particles collected during rotation were removed from the vacuum chamber and examined with SEM. For the same period of rotation, the quantity and size of the debris collected in vacuum experiments were larger than those in the wet CO_2 experiments. The average length of vacuum wear particles was ≈0.3 - 0.5 mm while for wet CO_2 the length of the wear particles was ≈0.03 - 0.08mm. SEM of several particles from the wet CO_2 experiments are shown in Fig. 4. Fig. 5 shows details of the structure of two typical wear particles collected in a wet CO_2 experiment. The morphology of these particles suggests that they are rolled layers or rolled particles. Figure 6 shows a particle collected from a vacuum experiment. X-ray diffraction was taken from large individual particles by mounting them on a glass fiber and by using a transmission pinhole technique. The very small particles were difficult to mount in such a way and therefore their individual diffraction patterns were studied by TED. The results from X-ray diffraction studies of large particles were identical to those obtained by TED from small particles. Fig. 7 shows a TED pattern obtained from a small particle. The absence of preferred orientation is apparent.

Figures 8 and 9 show typical SEM pictures of brush tracks on slip rings rotated in vacuum and in wet CO_2 respectively. The surface from the vacuum experiment shows deep grooves and high

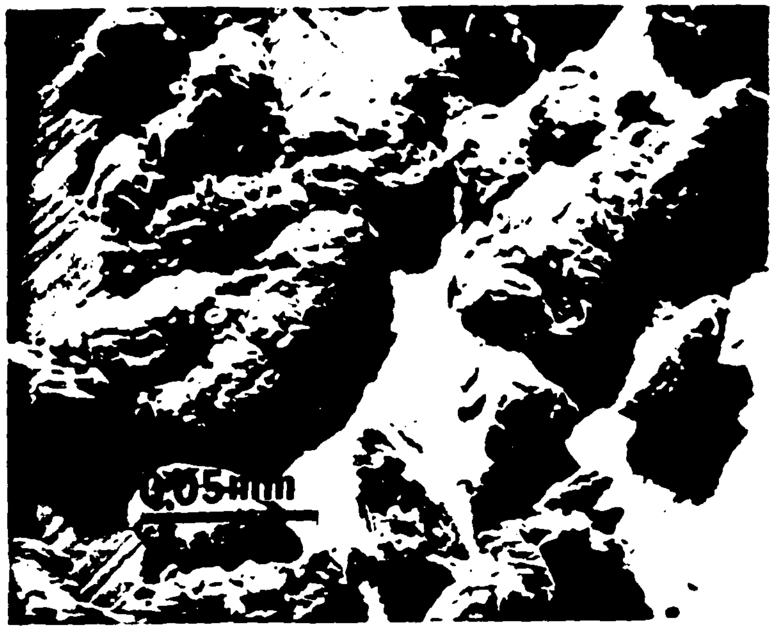

Fig. 4 SEM of copper wear particles collected during slip ring rotation in contact with brushes in wet CO_2.

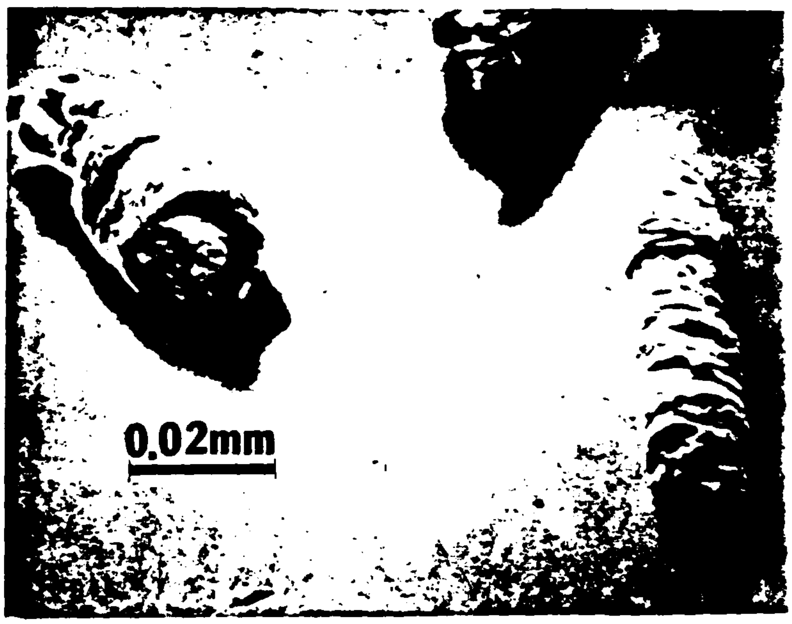

Fig. 5 SEM of copper wear particles collected during slip ring rotation in contact with brushes in wet CO_2.

ridges and several pieces of brush wire wear particles adhering to the surface. The wet CO_2 rotated surface shows shallow grooves and low ridges with a few occasional deep ridges. Also

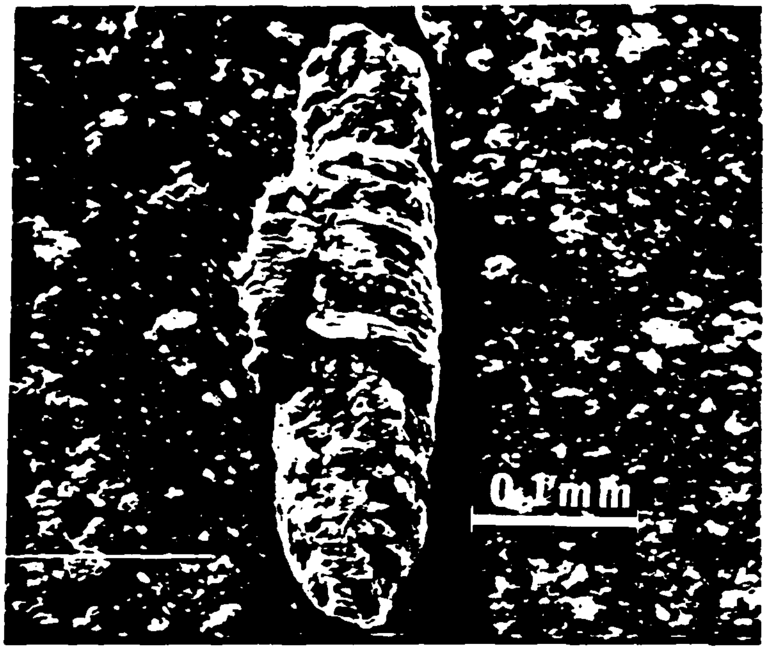

Fig. 6 SEM of copper wear particle collected during slip ring rotation in contact with wire brushes in vacuum. Note particles of silver paint on the substrate.

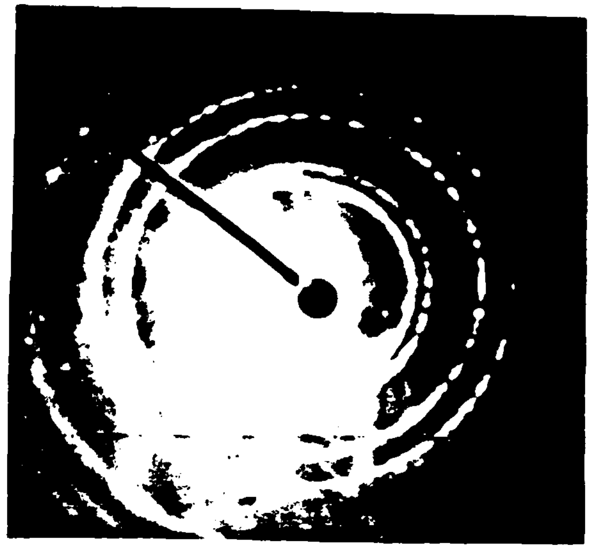

Fig. 7 TED of a small wear particle collected while the slip ring rotated in contact with a wire brush in wet CO_2.

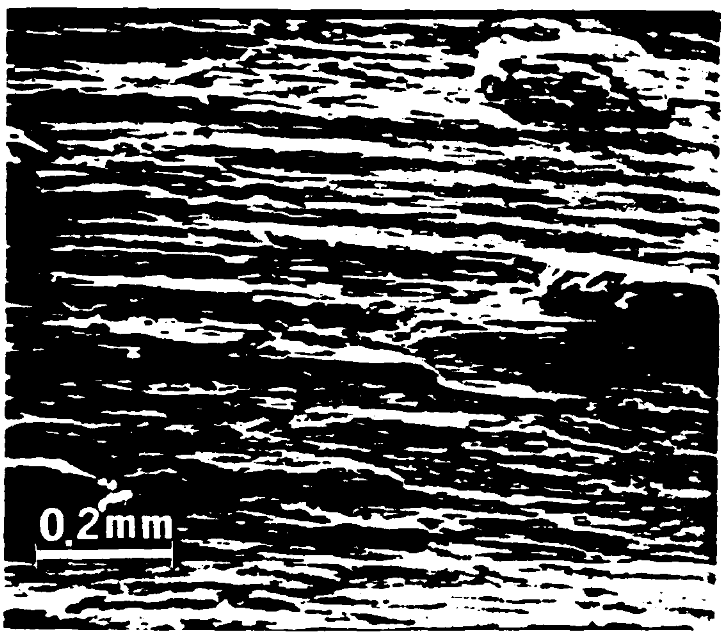

Fig. 8 SEM of OFHC Cu slip ring, upper track, showing broken wire pieces W and deep ridges. Arrow gives direction of relative brush motion (high vacuum).

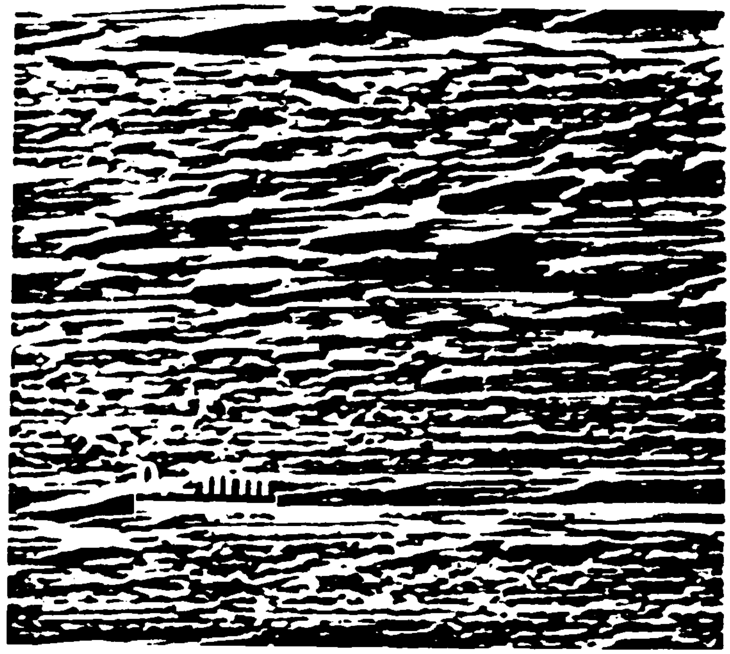

Fig. 9 SEM of OFHC Cu slip ring, upper track, showing shallow ridges. Arrow gives direction of relative brush motion. (wet CO_2).

no wear particles are observable. The ridges shown in these micrographs lie parallel to the directions of travel. SEM pictures of brush ends are shown in Figs. 10 and 11 for vacuum and wet CO_2 experiments. The vacuum contact brush wire ends appear very rough and abruptly broken, while the wet CO_2 contact brush wire ends are much smoother and of round shape. In Fig. 11 two regions S and R are clearly seen on the wire ends. The smooth (S) regions which touched the slip ring and the rough (R) and long streaked regions which were produced by the initial emergy paper polishing prior to insertion in the UHV chamber. These latter regions apparently did not touch the slip ring during rotation.

DISCUSSION

The elemental surface compositions of OFHC Cu slip rings that rotate in contact with two high purity Cu wire brushes in vacuum and in one atmosphere of wet CO_2 are presented. In vacuum, the initial conventionally cleaned surfaces (Cu 50 a/o) became almost completely clean (98 a/o) after several hundred rotations. Carbon was the major impurity observed. As the surface became cleaner with continued rotation, adhesion, friction and occasional cold welding started to develop. The occasional and erratic stick-slip resulted in large momentary fluctuations in contact resistance. Finally the adhesion became so large that the motor rotating the slip ring could not overcome the frictional torque, and cold welding occurred.

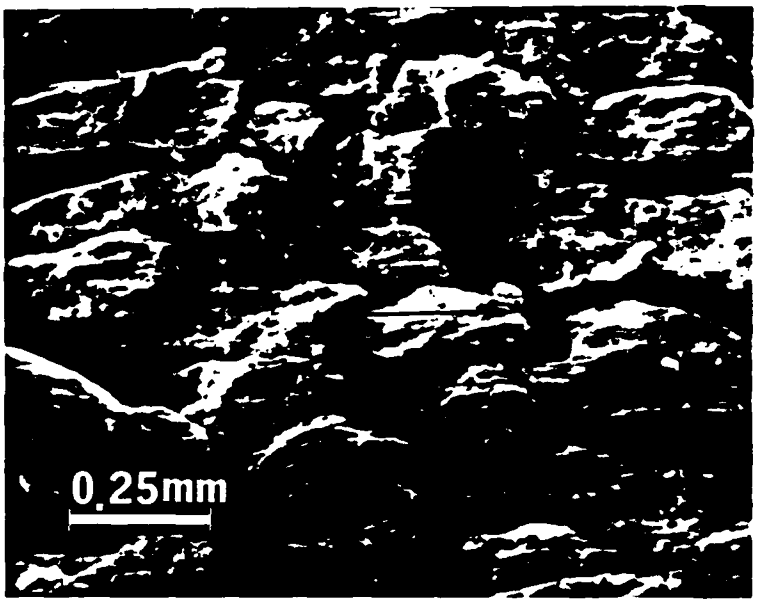

Fig. 10 SEM of wear surfaces on upper brush copper wires (contact force 235 gms.). Arrow gives the direction of relative motion of the slip ring (high vacuum).

Fig. 11 SEM of wear surfaces on upper brush copper wires (contact force 51 gms.). Arrow gives the direction of relative motion of the slip ring (wet CO_2).

In the case of rotation in wet CO_2 the surface also became clean except for the development of a slight S and C contamination. The studies involving a flat OFHC Cu sample (see section B of Results) suggest that the S came from an impurity in the CO_2 gas and not as a result of bulk segregation (14). The carbon concentration was of the same order as that observed in the vacuum experiments. Thus running in wet CO_2 contributed no additional C to the surface. In wet CO_2, the rotational speed of the slip ring increased and became steady after a few hundred rotations. Cold welding did not occur. These results indicated that the wet CO_2 environment provided good lubrication (3,4). The AES composition of the wet CO_2 surface was taken only when the wet CO_2 was pumped down to the 10^{-8} torr region which usually took about 30 hours. This result means that the H_2O - CO_2 mixture was not very tightly bound to the surface. It is well known that CO_2 is not chemisorbed on Cu and its maximum heat of physical adsorption (15) on metals is about 9 kcal/mole. Water, on the other hand, has a heat of adsorption of about 22-24 kcal/mole and is notoriously difficult to remove at room temperature (16). Thus CO_2 is pumped out much faster than H_2O, as was also observed by the mass spectroscopy analysis of the residual gas. It is thus expected that the H_2O molecules aid in the adsorption of CO_2.

The thickness of the H_2O - CO_2 interfacial layer would be expected to depend on the contact pressure. This result is in agreement with the contact resistance measurements, where the higher

normal forces have lower contact resistances. Thus the interfacial resistance appears to arise from a combination of quantum mechanical tunneling through the CO_2 - H_2O layer as well as occasional direct brush-slip ring contact, resulting in adhesion and fracture of plastically deformed surface regions. The net effect is that wear particles are formed. A determination of the approximate layer thickness h can be made from an empirical relation (17) [$R_f = \frac{\rho_t \xi H}{F}$, where ρ_t is the tunnel resistivity, ξ is a pressure factor ≈ 0.7 and H is the contact or penetration hardness) based on a tunneling conduction mechanism together with an experimental relationship between ρ_t and h (18). The results are approximate but indicate that the H_2O - CO_2 layer is about 6 Å thick for a 2.2 mΩ film resistance (R_f) and 80 gms of normal force (F). This result is reasonable since it implies a one to three molecule thick layer of CO_2 - H_2O. The thickness of the layer also depends on the orientation of the molecules with respect to the substrate as well as with respect to each other. It is thus concluded that the contact resistance at the Cu-Cu interface in wet CO_2 is not due to contamination by carbon or other impurities, but rather arises from the presence of this H_2O - CO_2 layer at the interface. The low contact resistance in vacuum arises from direct metal-metal contact. It decreases during rotation because the initial surface impurities are buried during rotation or possibly partially removed by the fallen wear particles and also because the surface contact area increases.

Formation of the wear particles and the ridges on the slip ring surface are of much interest. In vacuum, deep ridges arise from brush end ploughing and/or random localized welding of brush wire ends to the slip ring during rotation, resulting in tensile plastic deformation of the weld and then final fracture of the weld material or wire. Continued rotation may pull out some of these broken wire ends or material from the protruded ridges. These pieces then roll over between the brush-slip ring interface and eventually fall away from the interface. Clearly the wear particles in the vacuum case would be larger in size than those produced on occasional localized metal-metal contact through the thin CO_2 - H_2O layer where the weld area is likely to be smaller. This result is what has been observed experimentally. The average length of the vacuum wear particles is 0.3 - 0.5 mm and their diameter is 0.09 - 0.12 mm. The wet CO_2 wear particles have average lengths of 0.03 - 0.8 mm and diameters of 0.02 - 0.04 mm.

The morphologies of the wear particles are more or less the same. Some are made of thin layers rolled as sheets and some with more compacted but still rolled surfaces. There appears to be some relationship between the size of the wear particles, the ridges and the diameter of the brush wires. The average height of the broken wire pieces shown in Fig. 8 (vacuum) is about 0.09 - 0.13 mm, which is close to the diameter of the wires of the brush. It is thus reasonable to suppose that these pieces are parts of the broken wire which cold welded to the slip ring surface as it became cleaner in vacuum. In Fig. 9 (wet CO_2) the lengths of the well defined ridges vary from about 0.02 to 0.2 mm. The estimated unfolded length of the layer making up the particle in the upper left corner of Fig. 5 is about 0.09 mm, which is within the range of the length of the ridges in Fig. 9. Therefore, it is possible that this particle originally came from the slip ring surface, rather than from the wire of the brush. The variation in the length of the ridges could be due to variations in contact force at individual wire ends of the brush. The ridges may be formed by the ploughing action of the wire ends through the surface material of the slip ring. Continued rotation in the case of wet CO_2 tends to smooth these ridges, resulting in burnishing. The vacuum rotated surface has deep and sharp ridges because erratic cold welding prevented burnishing from occurring.

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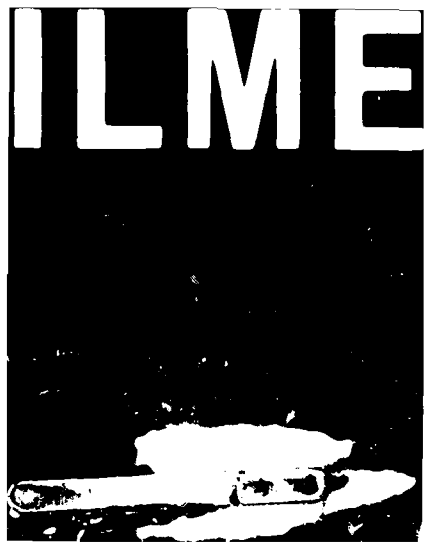
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